REPORT RESUMES

ED 018 097 EF 001 556

ACOUSTICS IN ARCHITECTURAL DESIGN, AN ANNOTATED BIBLIOGRAPHY ON ARCHITECTURAL ACOUSTICS.

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REPORT NUMBER BIB-NO-29 PUB DATE JAN 65

EDRS PRICE MF-$2.00 HC-$20.76 515P.

DESCRIPTORS- *ACOUSTICS, *ARCHITECTURE, *AUDITORIUMS, *FACILITY GUIDELINES, *PHYSICAL DESIGN NEEDS, BUILDING DESIGN,

THE PURPOSE OF THIS ANNOTATED BIBLIOGRAPHY ON ARCHITECTURAL ACOUSTICS WAS--(1) TO COMPILE A CLASSIFIED BIBLIOGRAPHY, INCLUDING MOST OF THOSE PUBLICATIONS ON ARCHITECTURAL ACOUSTICS, PUBLISHED IN ENGLISH, FRENCH, AND GERMAN WHICH CAN SUPPLY A USEFUL AND UP-TO-DATE SOURCE OF INFORMATION FOR THOSE ENCOUNTERING ANY ARCHITECTURAL-ACOUSTIC DESIGN PROBLEM, (2) TO CLASSIFY THE ENTIRE FIELD OF ARCHITECTURAL ACOUSTICS INTO A COMPREHENSIVE SYSTEM WITHIN WHICH EVERY RELATED TOPIC HAS ITS DISTINCT PLACE, AND (3) TO STRESS THE CLOSE RELATIONSHIP BETWEEN ACOUSTICAL PERFORMANCE AND ARCHITECTURAL EXPRESSION THROUGHOUT THE ENTIRE FIELD OF ARCHITECTURAL ACOUSTICS. THE DOCUMENT IS DIVIDED INTO THREE PARTS AS FOLLOWS--(1) ARCHITECTURAL ACOUSTICS IN GENERAL, (2) ROOM ACOUSTICS--AUDITORIA FOR SPEECH, ROOMS FOR MUSIC, PLACES FOR ASSEMBLY WITH MIXED ACOUSTICAL REQUIREMENTS AND STUDIOS, AND (3) NOISE CONTROL. THE THEORETICAL ASPECTS OF ARCHITECTURAL ACOUSTICS AND ALSO MATHEMATICAL RELATIONSHIPS HAVE BEEN REDUCED TO A MINIMUM IN THE ANNOTATIONS. IN THE PREPARATION OF THIS DOCUMENT, PARTICULAR ATTENTION HAS BEEN GIVEN TO THE SPECIFIC NEEDS OF THOSE RESPONSIBLE FOR BUILDING DESIGN. THIS DOCUMENT IS AVAILABLE FOR $4.00 FROM THE NATIONAL RESEARCH COUNCIL OF CANADA, DIVISION OF BUILDING RESEARCH, OTTAWA 7, ONTARIO. (RK)

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Acoustics
in
Architectural Design

Ottawa January 1965 $4.00 NRC 8358

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ACOUSTICS IN ARCHITECTURAL DESIGN

(An annotated bibliography on architectural acoustics)

by

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Bibliography No. 29
of the
Division of Building Research

Ottawa, January 1965

EF 001556

PREFACE

The Division of Building Research of the National Research Council of Canada gladly includes this annotated bibliography in its series of publications as a part of its share in this joint venture with McGill University.

Architectural acoustics is a subject of growing importance in Canada and is an important subject in the Division's research program. DBR/NRC was, therefore, glad to co-operate with Professor John Bland, Director of the McGill School of Architecture, and the author, in the work resulting in this publication and to provide some financial assistance.

The author is an acoustical consultant of Montreal who now lectures on architectural acoustics at both McGill University and the University of Montreal. The work represented by this Bibliography was carried out at McGill University in partial fulfillment of the requirements for the degree of Master of Architecture, a degree which he now holds.

The finished Bibliography is considered by the Division to be of real value. It is hoped, and indeed expected, that this volume will prove of value to architects and all concerned with architectural acoustics not only in Canada but wherever attention is being given to the improvement of acoustics as a part of the steady advance of building design.

January 1965

Robert F. Legget
Director
Division of Building Research
National Research Council

ACKNOWLEDGEMENTS

I am indebted to Professor John Bland, Director of the School of Architecture, and to Dr. Frederick S. Howes of the Department of Electrical Engineering, both of McGill University, for their general guidance throughout my postgraduate work at McGill University.

My special thanks are due to Robert J. Cook, architect, for giving his extraordinary care and attention to the considerable work that has been involved in reviewing the typescript and in making positive suggestions for improvements. Special credit must be given to Crispin Rhodes, a most able photographer, who gave me valuable help with his prompt and excellent photographic work. I am grateful to Marlene J. O'Brien who reviewed the final typescript.

I acknowledge my indebtedness to Donald G. McKinstry, Chief Architect, and Jean Rudinsky, Librarian, both of the Canadian Broadcasting Corporation, for their assistance given to me during the preparation of this study.

I wish to express my appreciation to the National Research Council of Ottawa whose generous grant enabled me to prepare this annotated bibliography. Dr. T. D. Northwood, of the Division of Building Research, NRC, has given me most valuable advice throughout the whole work.

Finally, I must add more than a word of gratitude to my wife Eva, Librarian of the Blackader Library of McGill University. In addition to producing the typescript, her great experience and untiring efforts over a period of almost two years have contributed to the completeness of this bibliography.

January 1965 Leslie L. Doelle

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LIST OF ABBREVIATIONS

used in the "References" and "GENERAL BIBLIOGRAPHY"

Acoust. Soc. Am. - Acoustical Society of America
Akust. Zeits. - Akustische Zeitschrift
Am. J. Phys. - American Journal of Physics
Ann. Télécomm. - Annales des Télécommunications
Arch. - architect(s); Architectural
Arch. Bât. Constr. - Architecure Bâtiment-Construction
Arch. Des. - Architectural Design
Arch. Forum - Architectural Forum
Arch. Rec. - Architectural Record
Arch. Rev. - Architectural Review
Archs.' J. - The Architects' Journal
Arch. Tech. Mess. - Archiv für Technisches Messen
ASHAE - American Society of Heating and Air-Conditioning Engineers
ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM - American Society for Testing Materials
Audio Engng. - Audio Engineering
Australian J. Appl. Sci. - Australian Journal of Applied Science
Baupl. Bautechn. - Bauplanung und Bautechnik
BBC - British Broadcasting Corporation
BBC Quart. - The BBC Quarterly
Bul. - Bulletin
Bul. AIA - Bulletin of the American Institute of Architects
Bul. de l'Assoc. Suisse des Élec. - Bulletin de l'Association Suisse des Électriciens
Can. Arch. - The Canadian Architect
CBC - Canadian Broadcasting Corporation
CBS - Columbia Broadcasting System
Comm. Sci. Ind. Res. Org. - Commonwealth Scientific and Industrial Research Organization
Elec. Commun. - Electrical Communication
Engng. - Engineering
Engng. News Rec. - Engineering News Record
HF. Électr. Courants Faibles - HF; Électricité, Courants Faibles, Électronique
Hochfreq. Tech. Elektr. Akust. - Hochfrequenztechnik und Elektroakustik

J.	Journal
J. Acoust. Soc. Am.	The Journal of the Acoustical Society of America
J. AIA	Journal of the American Institute of Architects
Japan Arch.	The Japan Architect
J. Appl. Mechanics	The Journal of Applied Mechanics
J. Appl. Phys.	Journal of Applied Physics
J. Audio Eng. Soc.	Journal of the Audio Engineering Society
J. Brit. Sound Rec. Assoc.	Journal of the British Sound Recording Association
J. IEE	Journal of the Institution of Electrical Engineers
J. IHVE	Journal of the Institution of Heating and Ventilating Engineers
J. Inst. Telecomm. Eng.	Journal of the Institution of Telecommunication Engineers
J. RAIC	Journal of the Royal Architectural Institute of Canada
J. Res. Nat. Bur. Stand.	Journal of Research of the National Bureau of Standards
J. RIBA	Journal of the Royal Institute of British Architects
J. Roy. Soc. Arts	Journal of the Royal Society of Arts
J. Roy. Soc. Health	Journal of the Royal Society of Health
J. Sci. and Ind. Res.	Journal of Scientific and Industrial Research
J. SMPE	Journal of the Society of Motion Picture Engineers
J. SMPTE	Journal of the Society of Motion Picture and Television Engineers
L'Arch. d'Auj.	L'Architecture d'Aujourd'hui
L'Arch. Fr.	L'Architecture Française
Nat. Bur. Stand.	National Bureau of Standards
NWDR	Nordwestdeutscher Rundfunk
Philips Tech. Rev.	Philips Technical Review
Proc. IEE	The Proceedings of the Institution of Electrical Engineers
Proc. IRE	Proceedings of the Institute of Radio Engineers
Proc. Phys. Soc. Lond.	Proceedings of the Physical Society of London
Progr. Arch.	Progressive Architecture

RCA - Radio Corporation of America
Rev. - Revue
Rev. Sci. - Revue Scientifique
Rundfunktech. Mitt. - Rundfunktechnische Mitteilungen
Schw. Arch. f. Angew. Wiss. u. Tech. - Schweizer Archiv für Angewandte Wissenschaft und Technik
Schweiz. Bauztg. - Schweizerische Bauzeitung
Tech. - Technical; Technische; Technik
Tech. Hausmitt. NWDR - Technische Hausmitteilungen des Nordwestdeutschen Rundfunks
Tech. Mitt. BRF - Technische Mitteilungen des Berliner Rundfunks
Tech. News Bul. Nat. Bur. Stand. - Technical News Bulletin of the National Bureau of Standards
Tech. Rev. - Technology Review
Veröff. Inst. Tech. Phys. - Veröffentlichungen aus dem Institut für Technische Physik
Z. Angew. Phys. - Zeitschrift für Angewandte Physik
Zeits. f. Techn. Physik - Zeitschrift für Technische Physik

INTRODUCTION

The enormous increase of noise sources inside and outside our buildings, the simultaneous shift from heavy, traditional building constructions to thin, light-weight, moveable and prefabricated building elements, in conjunction with the growing demand for improved hearing conditions in Auditoria, have made architectural acoustics an essential component in the environmental control of buildings.

Architectural acoustics, in both the fields of scientific research and practical application, has progressed further in the past few decades than during all preceding time, and consequently the amount of pertinent literature has reached an unprecedented high. It seemed to be worthy, therefore, to prepare an annotated bibliography on architectural acoustics for the assistance of those involved in architectural design problems, i.e., the architect, the engineer (mechanical and structural), the town planner, the builder, and the student of architecture and architectural acoustics. Less directly this work will be of value to anybody interested in the practical application of acoustics.

In compiling this annotated bibliography it was not intended to add another reference book on architectural acoustics to those already available, instead, the purpose was:

(a) to compile a classified bibliography, including most of those publications (books, booklets, articles, research papers, reports, bulletins, pamphlets, standards, codes, etc.) on architectural acoustics, published in English, French, and German which, in the writer's opinion, can supply a useful and up-to-date source of information for those encountering any architectural-acoustical design problem;

(b) to classify the entire field of architectural acoustics into a comprehensive system within which every related topic has its distinct place; and

(c) to stress the close relationship between acoustical performance and architectural expression throughout the entire field of architectural acoustics.

The bibliography is, therefore, the essential part of this work and in order to ensure its efficient use, it has been divided into several parts called "References", each one attached to the corresponding Section. Thus, for example, bibliographical entries related to Section G, "Acoustical Design of Rooms for Speech", will be found at the end of Section G. Whenever the text refers to an entry in the "References", the letter designating the relevant Section will be used hyphenated to the item number of the respective bibliographic entry in question; for example, "J-76" refers to the 76th entry within the "References" listed at the end of Section J, "Acoustical Design of Studios" ("Broadcast Studio Redesign by L.L. Beranek. J. SMPTE, vol. 64, Oct. 1955, p. 550-559.").

Near the end of this work a "GENERAL BIBLIOGRAPHY" will be found, listing various publications of universal scope on architectural acoustics. When referring in the text to entries of this "GENERAL BIBLIOGRAPHY", the letters GB will be used, hyphenated to the item number of that particular bibliographic entry in question; for example, "GB-43" refers to the 43rd item of the "GENERAL BIBLIOGRAPHY" ("Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys. Frederick A. Praeger, New York, 1958, pp. 331").

By and large, the "References" and the "GENERAL BIBLIOGRAPHY" contain most of the publications written on architectural acoustics published after 1940 in the English, French and German languages. However, some publications, written before 1940, which either supply in some way useful information or are of significance in the development of certain aspects in architectural acoustics, have also been incorporated in this work.

Of the publications which deal with identical or similar subjects, only those have been included in the "References" which, in the writer's opinion, are the most instructive. Publications discussing subjects of purely local interest or without noteworthy contribution to the solution of problems in architectural acoustics have been omitted from the "References".

Due to the large number of entries included in the "References" and considering the fact that the time allotted by the designers of buildings for research in the technical literature is usually very limited, it seemed to be advisable to mark with "+" those entries which, from a purely practical point of view, are particularly recommended for reading. This marking, however, does not intend to suggest a qualitative rating of the publications. The reading of the publications listed without this mark is equally recommended, if the reader has sufficient time to do so.

Abbreviations used in the "References" and in the "GENERAL BIBLIOGRAPHY" have been listed previous to this Introduction.

Quick reference to any subject in architectural acoustics can be found either by the use of the "Table of Contents" or through the "Subject Index" at the end of this work.

This annotated bibliography has been divided into three parts, as follows:

PART I. ARCHITECTURAL ACOUSTICS IN GENERAL. This part

- outlines the significance of acoustics in architectural design and determines its position within the environmental control of buildings;
- points to noteworthy achievements in the history of architectural acoustics; and
- discusses briefly acoustical relationships and terms of importance (such as frequency, loudness, the ear and hearing, timbre, masking, etc.) which will be used or referred to in succeeding Sections.

PART II. ROOM ACOUSTICS. This part

- deals with acoustical phenomena in enclosed spaces (such as sound reflection, sound absorption, reverberation, diffusion, etc.);
- classifies and describes the materials and constructions used for architectural-acoustic purposes;
- discusses acoustical requirements in Auditorium design;
- divides the architectural spaces, used for listening purposes, into four groups: (1) Auditoria for speech, e.g., Theaters, Lecture Halls, Congress Halls, Conference Rooms, etc.; (2) Rooms for music, such as Concert Halls, Opera Houses, etc.; (3) Places of assembly with mixed acoustical requirements, i.e., used for speech and music, such as Churches, Motion Picture Theaters, Open-Air Theaters, etc.; (4) Studios, requiring special consideration and care in their acoustical design, such as Radio and Television Studios, etc.;
- describes ways in which the acoustics of an Auditorium can be checked during the design stage and after the completion of the building;
- gives information on sound amplification systems used in various Auditoria.

PART III. NOISE CONTROL. This part

- refers to the general principles of noise control and advises on the methods to be followed in the elimination or reduction of noises in buildings;
- deals with sound insulating building constructions, such as, walls, floors, doors and windows, and calls attention to the factors affecting the acoustical performance of these enclosures;
- outlines the control of mechanical noises and vibrations due to water systems, ventilating and air-conditioning equipment and machinery;

- surveys the various noise criteria usually discussed in the literature and used in practice;
- describes practical aspects to be followed in the noise control of various types of buildings; such as, Auditoria, Residential Buildings, Schools, Hospitals, Offices, Sound Laboratories, Industrial Buildings, etc.

For practical reasons, theoretical aspects of architectural acoustics and also mathematical relationships have been reduced to a minimum in the annotations.

Experience has proven that the acoustical performance of a building will eventually depend on the attention that has been given by the designer to acoustical aspects in the design, detailing and specifying of that particular job. To do so, the designers of the buildings must have a basic understanding of the relevant architectural acoustical principles and their appropriate application. It is for this reason that in the preparation of this annotated bibliography particular attention has been given to the specific needs of those responsible for building design. Although it may be necessary to retain the services of a competent acoustical consultant, it rests with the architect to see that acoustical requirements are recognised and respected in the initial stages of architectural design. Society rightfully expects that ideal environmental conditions, essential to our comfort, health and happiness, and necessary to free our energies for productive work, be achieved in our buildings by their designers.

PART I.
ARCHITECTURAL ACOUSTICS IN GENERAL

Section A. Significance of Acoustics in Architectural Design

A.1 The place of architectural acoustics in the environmental control of buildings

A.2 Acoustical problems in contemporary architectural design

References

A.1 The place of architectural acoustics in the environmental control of buildings

The remarkable development of the engineering sciences has reached the stage where, in today's architectural practice, a building does much more than simply provide shelter and protection for its occupants against the extremities and fluctuations (thermal, atmospheric, sonic, luminous and spatial) of the exterior world. Contemporary environmental control can create a complex, artificial environment in buildings, that will meet all the physical, physiological and psychological demands of the occupants. This artificially-created, "synthetic" environment is, therefore, in many respects superior to the natural one.

Thus, Sound Control, constituting a branch in the environmental control of buildings, can create an artificial sonic environment in which:

(a) ideal hearing conditions will be provided both in enclosed spaces and in the open air; and

(b) the occupants of the buildings will be adequately protected against excessive noises and vibrations harmful to human well-being, health and productivity.

Accordingly, the sound control of buildings has two goals:

(a) to provide the most favorable hearing conditions for the production, transmission and perception of wanted sounds (speech, music, etc.) inside the rooms used for various listening purposes, or in the open air. This field of sound control is called ROOM ACOUSTICS and will be covered in Part II;

(b) the exclusion or reasonable reduction of noises (unwanted sounds) and vibrations. This range of sound control is termed as NOISE CONTROL and will be dealt with in Part III.

The problems of ROOM ACOUSTICS and NOISE CONTROL are naturally interrelated and interdependent, and cannot be separated from one another. As will be discussed later, the elimination of noise plays an important role in the room acoustical design of Auditoria; similarly, room acoustical problems are involved in the noise control of rooms.

A.2 Acoustical problems in contemporary architectural design

Continuous improvements during the last decade in building technology and a gradual shift in the basic concept of architectural design have made acoustics an important factor affecting the performance of architectural spaces (A-20). Following are the main factors which have made architectural acoustics a contributing participant in the environmental control of buildings (A-1, A-3):

(A) An incredible number of Auditoria (i.e., Theaters, Churches, Lecture Halls, Studios, Concert Halls, etc.) are being built all over the world. The large sizes and capacities of many of these Auditoria have created room acoustical problems which definitely could not have been resolved a few decades ago. In addition, the contemporary trend in architectural design practice of using plain, uninterrupted, hard (i.e., sound reflective) surface treatments with little, if any, ornamentation, has had a detrimental affect upon the acoustics of Auditoria.

(B) In the structural and constructional field there is a continuously and rapidly increasing use of light-weight building materials and constructions. Prefabricated elements are being used for both exterior and interior walls, for partitions, floors, and suspended ceilings

(A-21). Furthermore there is a growing demand for the flexibility and movability of partitions. All these elements lack the most important feature of an efficient sound insulating enclosure, i.e., mass. In addition, unfortunately, they do promote the harmful transmission of noise through gaps and open spaces created by the jointing of prefabricated elements and by the noise-radiating characteristics of thin, light-weight building panels.

(C) A gradual change can be observed in the basic concept of architectural design. This trend advocates that spaces in a building, instead of being separated from one another, should be rather integrated into visually undivided, large units without enclosures, continuing through open screens, grilles, space dividers, glazed barriers and curtain walls (A-20). Even though this design concept generally creates pleasant interiors, it must be noted that the desire for open plans and undivided interior spaces conflicts with the exclusion of unwanted, penetrating noises and brings about noise control problems (A-21).

(D) In the mechanical field the buildings are becoming increasingly mechanized; many components of the heating, ventilating and air conditioning systems (fans, diffusers, compressors, cooling towers, etc.), the various work machines (such as typewriters, computers, etc.) and also various household articles of equipment unfortunately all contribute to the noise pattern of a building (A-16). A contemporary office building is, in fact, entirely interwoven with a most comprehensive network of noise and vibration transmitting ducts, shafts, cables, conduits, wiring, etc. (A-21). In addition to these interior (mechanical) noises new exterior noise sources are coming into existence, originating from the existing and new industries and from transportation (jets, trucks, etc.). The exclusion or reasonable reduction of these interior and exterior noises constitutes a serious acoustical problem.

The increasing demand for various Auditoria all over the world involves not only quantitative but also qualitative requirements. No longer will an audience or a professional critic excuse the erection of an Auditorium having any serious acoustical defect. Church Halls, built in the past with long reverberation times for services in which musical and choral presentations prevailed, today are also used for sermons with special emphasis laid on the intelligibility of the speech. It is a difficult problem, even for a qualified acoustical expert, to provide equally favorable hearing conditions within the same Church Hall for organ, choir and sermon alike, without altering the reverberation time. Large multi-purpose Auditoria are today utilized - mainly due to box-office policy - for a multitude of purposes; such as,lectures, political rallies, panel discussions, recitals, stage presentations, concerts, etc. The manifold use of the same Auditorium imposes a particular task upon the designers which under normal economic conditions can be solved by an acoustic compromise only (A-25).

Two circumstances are effectively contributing to the evolution of satisfactory solutions for the diverse acoustical problems in architectural design:

(A) Since the turn of the 20th century, but particularly in the last few decades, a large amount of theoretical and practical research work has been conducted in North America, Europe and Australia, the results of which have been published and constitute an important part of the References and GENERAL BIBLIOGRAPHY of this work (A-19).

Furthermore a large range of electronic instruments has become available that has enabled us to find answers to previously unknown acoustical phenomena, many of which had been labelled before as mysterious.

(B) Simultaneously, the mass production of acoustical materials provides us with the necessary means to control the various acoustical defects in rooms.

Clearly designers of buildings must possess a basic understanding of the acoustic principles and requirements if they are to solve their pertinent problems (A-2, A-9). They must remember that it is not the acoustic treatments alone which affect hearing conditions in a room. The acoustics of any Auditorium will be considerably affected by a series of seemingly purely architectural considerations with regard to room shape, room proportions, layout of enclosures, dimensions and distribution of exposed structural elements (A-16), surface irregularities, fixtures, seating layout and capacity, decorations, etc. (A-25). Practically,every detail within the enclosed space contributes to a greater or lesser extent to the acoustical performance of that particular Auditorium.

The design of an acoustically efficient sound insulating enclosure will require equally special attention on the part of the designer. It is not only the material proper of that particular enclosure that determines efficiency of acoustical insulation but other aspects; such as,connections to adjacent enclosures, construction joints left unfilled between elements and around doors, windows, fixtures, pipes or other equipments that penetrate the enclosure or surface treatment. These details, and others,do affect the sound insulation performance of any enclosure.

The designers of buildings can be assured that the workmanlike solution of acoustical requirements does not curtail or even restrict their design freedom. All acoustical problems can be attacked in a number of ways. Contemporary constructional and interior decorating practice permits that acoustical principles and requirements be satisfactorily translated into the language of good architecture (A-18, A-20).

A number of practical examples of Auditoria that combine high acoustical performance with distinctive architectural expression will be referred to later in this work.

References

relative to Section A, "Significance of Acoustics in Architectural Design"

(See list of abbreviations on page 1)

Books, chapters of books

+ A-1 American Building by J.M. Fitch. Houghton Mifflin Co, Boston, 1948, pp. 382.

+ A-2 Introduction and terminology (contained in "Handbook of Noise Control") by C.M. Harris. McGraw-Hill Book Co, New York, 1957, p. I.1.-I.19.

+ A-3 Environmental Technologies in Architecture by B.Y. Kinzey and H.M. Sharp. Prentice-Hall, Englewood Cliffs, New Jersey, 1963, pp. 788.

A-4 Human Engineering Guide to Equipment Design edited by C.T. Morgan et al. McGraw-Hill Book Co, New York, 1963, pp. 615.

Articles, papers, reports

+ A-5 Some cultural applications of modern acoustics by V.O. Knudsen. J. Acoust. Soc. Am., Vol. 9, Jan. 1938, p. 175-184.

A-6 Control of sound in buildings by Dr. P.E. Sabine and Dr. K.C. Morrical. Arch. Rec., Jan. 1940, p. 66-73.

+ A-7 Some practical aspects of architectural acoustics by V.O. Knudsen. J. Acoust. Soc. Am., Vol. 11, Ap. 1940, p. 383-389.

+ A-8 Planning functionally for good acoustics by J.P. Maxfield and C.C. Potwin. J. Acoust. Soc. Am., Vol. 11, Ap. 1940, p. 390-395.

A-9 Selected problems in architectural acoustics by M. Rettinger. Proc. IRE, Vol. 31, Jan. 1943, p. 18-22.

+ A-10 Silence: men at work (contained in "American Building") by J.M. Fitch. Houghton Mifflin Co, Boston, 1948, p. 250-266.

A-11 Architectural acoustics - new trends in teaching and research by R.H. Bolt and A.M. Clarke. Tech. Rev., Vol. 51, Mar. 1949, p. 279-280, 282.

A-12 Grundsätzliches zur Raumakustik by E. Skudrzyk. Acta Austriaca, Vol. 3, No. 2-3, 1949, p. 229-269.

+ A-13 Design for acoustics by L.L. Beranek. Physics Today, Vol. 2, July 1949, p. 19-22.

A-14 Architectural acoustics (in German) by E. Wintergerst. Z. Angew. Phys., No. 9, 1949, p. 428-436.

A-15 Role of acoustical design in planning of buildings by R.K. Vepa. J. Sci. and Ind. Res., Vol. 10, Mar. 1951, p. 105-108.

+ A-16 Making acoustical virtues out of architectural necessities by P.E. Sabine. J. Acoust. Soc. Amer., Vol. 27, May 1955, p. 497-499.

+ A-17 The engineer by J.M. Fitch. Arch. Forum, Mar. 1956, p. 106-111.

+ A-18 Ein Beispiel für die Zusammenarbeit zwischen Architekt und akustischer Berater by H. Dörge. Schalltechnik, Vol. 16, June 15, 1956, p. 1-9.

+ A-19 Beautiful buildings and horrible sounds. Arch. Forum, Sep. 1956, p. 152-157.

+ A-20 Needed: a building science. Arch. Forum, May 1958, p. 132-135, 206.

+ A-21 The ring of architecture by R.L. Geddes. Progr. Arch., May 1958, p. 144-145.

+ A-22 Acoustics for modern interiors by D. Allison. Arch. Forum, Vol. 110, Ap. 1959, p. 145-149.

A-23 Acoustic faults in contemporary architecture by S. Brown and A. Keith. New Scientist, Vol. 14, No. 292, 1962, p. 636-638.

+ A-24 Influence of acoustics on design and construction of buildings in America today by R.B. Newman. Congress Report No. M47, Fourth International Congress on Acoustics, Copenhagen, 1962, pp. 4.

+ A-25 Acoustics and the arts by D.W. Martin. Sound, Vol. 2, May-June 1963, p. 8-13.

+ A-26 Acoustics and architecture by R.B. Newman. Sound, Vol. 2, July-Ag. 1963, p. 15-17.

Section B. History of Architectural Acoustics

References

The Auditorium, as a place for hearing, has developed from the classical Open-Air Theaters; however, no reliable evidence exists that particular consideration was given to acoustical principles when natural sites were selected and Open-Air Theaters built by the Greeks and Romans (B-10).

There is a considerable literature on the acoustics of the ancient Open-Air Theaters (B-6, B-7, B-8, G-13, G-17, I-99, I-109) but probably too much credit is given to the Greeks and Romans for acoustical sense in planning. They may well have attempted to solve only the line-of-sight problem and just obtained reasonable hearing conditions at the same time. They tried to locate the audience as close as possible to the elevated acting area or "logeion" (speaking place) by shaping the steeply banked seating area in a semi-circle which naturally resulted in reasonably good hearing. Besides this, the performers used large masks partly to exaggerate their facial expressions and partly to reinforce their voice power. Later the Romans built large slanting roofs above and at both sides of the acting areas which provided efficient sound reflectors and resulted in at least moderately satisfactory intelligibility at the remote seats (B-10).

The Theater at Orange, in France, built about 50 A.D. by the Romans (Figure B.1) represents a typical example of the ancient Open-Air Theaters. The audience area is 340 ft in diameter and it has a large sound reflective canopy above the acting area (B-10, B-11, GB-21).

The first reference to architectural acoustics in recorded history is made by Vitruvius (1st century B.C.). In his book "De Architectura" he describes sounding vases ("echeia") as being used in certain Open-Air Theaters but no trace of these vases has ever been found in any ancient Theater.

The Middle Ages inherited from the classical times only an empirical knowledge of the acoustics of enclosed spaces, consequently, the acoustics of medieval Church Halls, except those

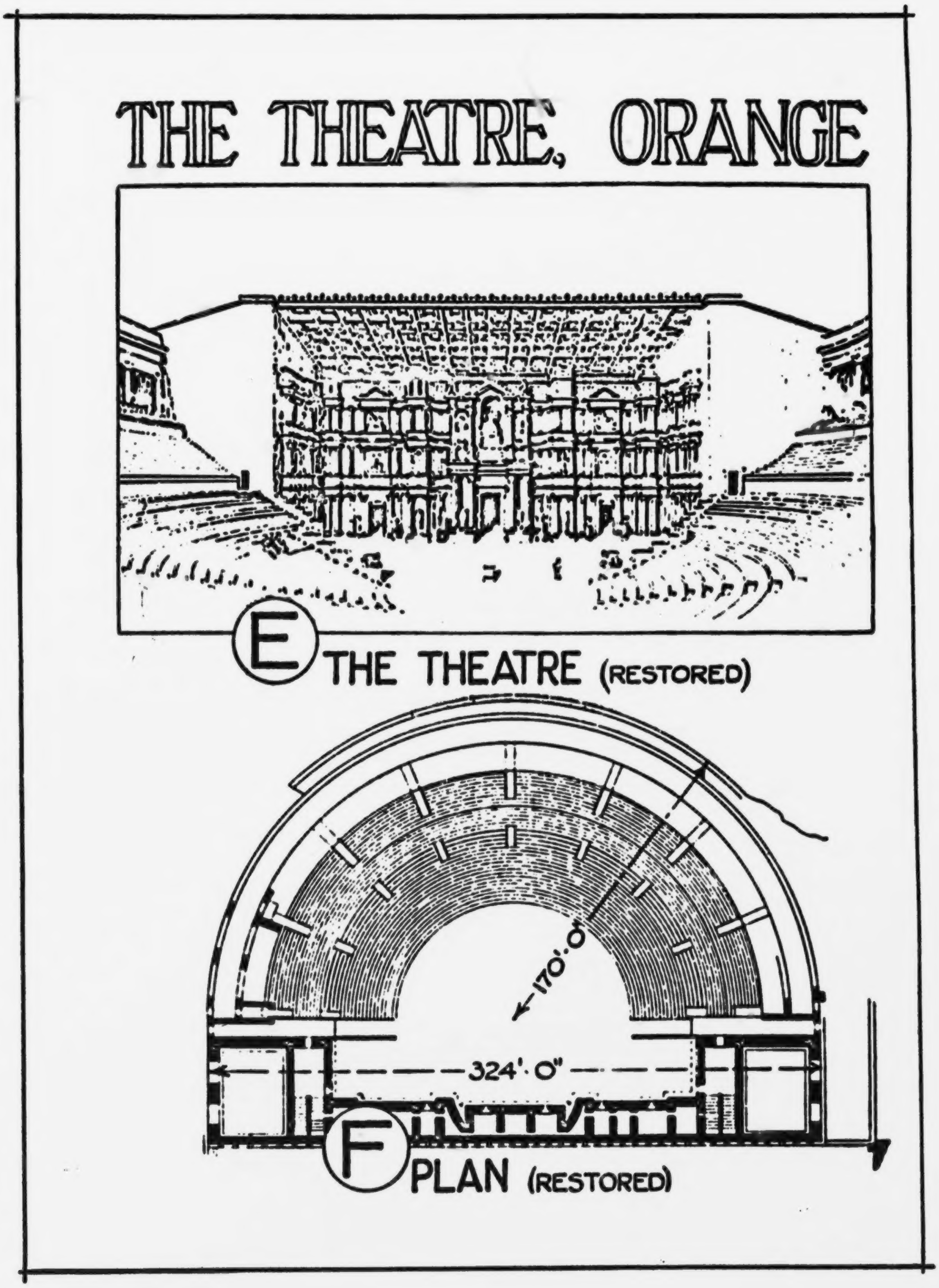
THE THEATRE, ORANGE
E
THE THEATRE (RESTORED)
170'·0"
324'·0"
F
PLAN (RESTORED)

Figure B.1. Theater at Orange (France), built about A.D. 50 by the Romans, representing a typical example of the ancient Open-Air Theaters. (Reprinted from A History of Architecture on the Comparative Method by B. Fletcher, B.T. Batsford, London, 1946).

small in volume and capacity, can be characterized by their overwhelming fullness of tone (see subsection H.1), excessive reverberation and poor intelligibility.

In subsequent centuries a remarkable number of Theaters were built, sometimes with surprisingly large capacities. The Teatro Olimpico at Vicenza (Italy), designed by Palladio and built in 1589 by Scamozzi, had an audience of 3000 (GB-42). The Teatro Farnese at Parma (Italy), designed by G.B. Aleotti and built in 1618, had a capacity of 2500. Available descriptions do not reveal any particular acoustical deficiencies of these and other contemporary Auditoria (G-13, G-17).

Until about the beginning of the 19th century, in the design of Auditoria used primarily for the performance of music (such as Churches, Opera Houses and Ballrooms), acoustical aspects of enclosed spaces, being entirely unknown to the designers, had to be subordinated to other interests. In fact, sound programs during these centuries (church music, chorale, opera, symphonic music, etc.) attempted to fit into the prevailing acoustical conditions of existing Auditoria. Bach's organ music (in the first half of the 18th century) was composed to fit the acoustics of Thomas Church in Leipzig (I-11, I-28, I-31). Baroque and classical music (represented by Händel, Mozart, Beethoven, etc., from 1600 to 1820) was written to fit the acoustical atmosphere of the ballrooms of the aristocrats. The sounds of the Italian Opera (represented by Donizetti, Rossini, Verdi, etc., in the 19th century) fitted into the acoustical environment of the horse shoe shaped Opera Houses of Milan, London, Paris, Vienna, New York, etc. (H-120, H-131, H-133, H-134, H-136, H-137, H-141). Composers of the romantic period (Mendelssohn, Brahms, Liszt, Debussy, Tchaikovsky, etc., 19th century) had the Concert Halls of Vienna, Leipzig, Glasgow, Basel, etc., in mind (H-22, H-59, H-83, H-88, H-93, H-98, H-106, H-110). Many of these 19th century Concert Halls represent - even to day - the greatest achievements of empirical acoustics before the enormous progress in the scientific research of the 20th century defined the problems of contemporary room acoustics (H-3, H-5, H-6).

The designers' attitude in the 19th century is best reflected in the following words of Charles Garnier, architect of the Paris Opera House (B-10): "I must explain that I have adopted no principle, that my plan has been based on no theory, and that I leave success or failure to chance alone" (C. Garnier: "L'Opera, Paris", 1880).

Before the 20th century only one Auditorium was acoustically designed in the sense that some consideration was given to acoustical requirements and this was Wagner's Festival Opera House, in Bayreuth, Germany, dedicated in 1876 (H-135, H-140).

In the second half of the 19th century Lord Rayleigh published his classical exposition on "The Theory of Sound", however, it was not until the advent of the 20th century that Prof. W.C. Sabine of Harvard University did his pioneer work on room acoustical design (B-2, B-3). It was he who first devised the coefficient of sound absorption and arrived at a simple relation between the volume of a room, the amount of sound absorbing material in it and its reverberation time. W.C. Sabine thus took Auditorium acoustics out of the realm of guesswork and established it as a systematic branch of engineering science.

From this start the new subject of architectural acoustics advanced rapidly. Scientists and engineers undertook theoretical and practical research work in room acoustics; its principles became established. A large range of electronic instruments became available enabling the physicists to find answers to previously unknown, sometimes mysterious acoustical problems, also in the field of auditory phenomena.

In the 30's of this century the cinema has found its voice (I-98). From this date the high quality recording, amplifying and reproducing of sound started to play an important role in several walks of the scientific, educational, cultural and social life. The extraordinary development of radio and television broadcasting has presented new acoustical problems to solve and aroused general interest in listening to music.

The mass production of architectural-acoustic materials has supplied the designers of buildings with the necessary means to control sound in architectural spaces. The number of Auditoria which are being built all over the world and require acoustical considerations, is virtually infinite.

Considering the formidable development of architectural acoustics, it is noticeable that in the first half of the 20th century progress was more pronounced in the field of room acoustics. However, in view of today's increasingly worsening noise conditions and also because of gradual introduction of thin, light-weight and prefabricated constructions in the building industry, it is anticipated (and in fact has already been experienced) that in the years to come a comparable progress will take place in the other, hitherto neglected offspring of architectural acoustics, i.e., noise control.

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(See list of abbreviations of page 1)

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Section C. Properties of Sound

C.1 Origin and propagation of sound. Speed of sound
C.2 Frequency, pitch, wavelength
C.3 Sound pressure, sound intensity, loudness
C.4 Acoustical power of sound sources
C.5 The human ear and hearing
C.6 Timbre
C.7 Directionality of sound sources
C.8 Masking
C.9 Sound and distance. Propagation of sound in the open air
References

C.1 Origin and propagation of sound. Speed of sound

The word "SOUND" has two definitions:

(a) physically speaking it is a fluctuation in pressure, a particle displacement in an elastic medium, like air; this is objective sound;

(b) physiologically it is an auditory sensation evoked by the fluctuation described before; this is subjective sound.

In this study SOUND will express an auditory sensation produced through the ear and created by fluctuations in the pressure of air (C-4, C-32). The fluctuations are usually set up by some vibrating object, e.g. a struck key of a piano or a plucked string of a guitar.

Sound wave motion is created by outwardly traveling layers of compression and rarefaction of the air particles, i.e. by pressure fluctuations (C-1). The air particles that transmit sound waves do not change their normal positions (C-2); they vibrate about their equilibrium positions only (which are their positions when no sound waves are transmitted). The pressure fluctuations are superimposed on the more or less steady atmospheric pressure and will be picked up by the ear.

A single, full displacement "activity" of the particle is called a cycle. The distance the particle moves from its rest position is called amplitude.

The speed of the sound wave motion at 68°F (20°C) room temperature is about 1130 ft per sec (344 m per sec). In later discussions it will be shown that it is this relatively low speed of sound that leads to the well known acoustical defects, such as echo and excessive reverberation.

C.2 Frequency, pitch, wavelength

The number of displacements (vibrations) that the particles undergo in one second is called frequency, usually stated in cycles per second (abbreviated cps or c/s); e.g., if a string undergoes 261 oscillations in one second (261 cps), it will produce in the eardrum of an observer the subjective tone of middle "C". Frequency is an objective physical phenomenon which can be measured by instruments (C-1, C-2, C-3).

The attribute of an auditory sensation which enables us to order sounds on a scale extending from low to high is called pitch. It is the subjective physiological equivalent of frequency. The pitch depends primarily upon the frequency of the sound stimulus (C-32).

A sound sensation having pitch is called tone. Pure tone (or simple tone) is a sound sensation of a single frequency characterized, therefore, by its singleness of pitch. It can be produced by striking a tuning fork. Complex tone is a sound sensation characterized by more than one pitch, e.g., that produced on musical instruments. Whether or not a person hears a tone as simple or complex depends on ability, experience and listening attitude.

The distance that a sound wave travels during each complete cycle of vibration, i.e., the distance between the layers of compression, is called wavelength. The following constant relationship exists between wavelength, frequency and speed of sound:

wavelength x frequency = speed of sound.

A normal ear responds to sounds within the audible (audio) frequency range of about 20 to 20,000 cps, however, frequencies higher than 10,000 cps are of negligible importance for the intelligibility of speech or for the enjoyment of even Hi-Fi music. This audio-frequency range varies remarkably with different people and different ages (C-7, C-10).

The wavelength of sounds within the frequency range of 20 to 10,000 cps extends from 56 ft to about 1". The consideration of the relationship between frequencies and wavelengths of sound waves is quite important in the acoustical design of Auditoria. Efficient sound absorptive, sound reflective or diffusive room enclosures have to be designed in a fashion so that their dimensions will be comparable to the wavelengths of those frequencies which have to be absorbed, reflected or diffused respectively.

C.3 Sound pressure, sound intensity, loudness

The fluctuation in the atmospheric pressure caused by the vibration of air particles due to a sound wave is called sound pressure, measured in dyn/cm^2. The ear responds to a very wide range of sound pressures, nevertheless the pressures themselves are small; e.g., at 1000 cps the faintest sound that will evoke an auditory sensation in the average person's ear must have a pressure of 0.0003 dyn/cm^2 (threshold of audibility), while sound waves with a pressure of 300 dyn/cm^2 will cause actual pain in the ear (threshold of pain). This means that the range of sounds which can be perceived by the human ear vary by a factor of one million in their pressure (C-1, C-4).

The dyn/cm^2 scale extends over a too wide range which makes it somewhat awkward to deal with it. Furthermore it does not take into account the fact that the ear does not respond equally to changes of pressures at all levels of intensity. For these reasons it seemed convenient to measure sound pressures on a logarithmic scale, called the decibel (abbreviated: dB) scale. This scale approximately fits the human perception of the loudness of sound which is roughly proportional to the logarithm of the sound energy. This implies that sound energies proportional to 10, 100, and 1000 would produce in the ear effects proportional to their logarithm, i.e., to 1, 2, and 3 respectively. If we multiply numbers of this logarithmic scale by 10, we have established the decibel scale. The unit of this scale, the decibel, is the smallest change in sound energy that the average ear can detect (C-25, N-95). The sound pressure measured on the decibel scale is called sound pressure level. Sound pressure and sound pressure level are pure physical quantities (C-5).

Sound pressure levels are measured by a sound level meter. This consists of a microphone, amplifier and output instrument which measures the effective sound pressure level in dB. Various accessories can be attached to or incorporated into the basic instrument, according to its required purpose; such as, frequency analyzer, weighting network, recorder, etc. Sound level meters, manufactured in various sizes and by many firms, can be used for a number of purposes in architectural acoustics; they provide an important instrument in the evaluation and control of noise and vibration.

The sound intensity in a specified direction at a point is the average rate of sound energy transmitted in the specified direction through a unit area normal to this direction at the point considered (C-32). Sound intensity is expressed in watt/cm^2. The reference intensity generally used for zero level is 10^{-16} watt/cm^2. The sound intensity levels are expressed in dB-s above this zero level. Multiplying the intensity by 10 at any point in the scale raises the sound level 10 dB. Doubling the intensity of sound at any point along the scale always raises the sound level about 3 dB (C-5). A 3 dB change in the sound level is generally perceptible, 5 dB is clearly noticeable. An increase of 10 dB sounds twice as loud, 15 dB means an appreciable change and an increase of 20 dB results in a sound very much louder than the original (GB-51).

Table C.1 lists examples of various sound intensities expressed in dB-s.

Table C.1 Intensities of various sound sources expressed in decibels.

Sound source	Intensity dB
Threshold of audibility	0
Quiet Church Hall	10
Rustle of leaves, average whisper	20
Average Auditorium	30
Average Office	40
Average Store	50
Office with typewriters	60
Average machine shop	70
Noisy street corner	80
Full volume radio music	90
Boiler factory	100
Orchestral music,fortissimo	110
Jet aircraft engine	120
Threshold of pain	130

Loudness is the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale, extending from soft to loud (C-32). It is the subjective response to sound pressure and intensity. The loudness level of a sound in phons is numerically equal to the sound pressure level (in dB, relative to 0.0002 dyn/cm^2) of a pure tone of 1000 cps frequency which is judged by listeners to be equally loud (C-2, C-32). The phon scale takes into account the varying sensitivity of the ear to sounds of different frequencies, consequently it is an objective measure (C-13, C-17).

The phon is the unit of loudness level, while the unit of the loudness itself is called sone (C-18, C-19). By definition, a simple tone of 1000 cps frequency, 40 dB above a listener's threshold of hearing, produces a loudness of 1 sone. The loudness of any sound that is judged by the listener to be "n" times that of the 1 sone tone is "n" sones (C-32).

C.4 Acoustical power of sound sources

The average acoustical power generated by all sound sources is surprisingly small. The acoustical power which a speaker has to produce in a room to make himself adequately understood will vary between 10 and 50 microwatts (usually depending on the size of the room), consequently the resulting sound pressure is very small.

The minute amount of acoustical power produced by a speaker will be illustrated by the following. The simultaneous loud speech of 4 million people would produce the power necessary to burn a single 40 watts light bulb; or, as Knudsen describes it, it would require no fewer than 15,000,000 speakers to generate a single horse power of acoustical energy (C-1).

A singing voice or a musical instrument radiates several hundreds or even thousands of microwatts acoustical power. This explains the ease with which a singer with his voice or a musician with his instrument's tone can fill the volume of an Auditorium that is otherwise too large for unamplified speech.

C.5 The human ear and hearing

When alternating pressures of a sound wave reach our outer ear, the vibrations received by the eardrum will be multiplied by means of small bones in the middle ear and transmitted through a fluid to nerve endings within the inner ear. The nerves finally transmit the impulses to the brain where the final process of hearing takes place; thus the sensation of sound is created (C-12, C-15, C-22, C-30, C-31).

The perception of the human ear, as mentioned before, is limited in range to frequencies between about 20 cps at the lower end and 20,000 cps at the higher end of the scale (C-7, C-10, C-15).

The minimum sound pressure level of a sound that is capable of evoking an auditory sensation in the ears of an observer was called in subsection C.3 the threshold of audibility. When the pressure of the sound is increased and the sound becomes louder and louder, eventually it will reach a level at which the sensation of hearing becomes uncomfortable. That minimum sound pressure level of a sound which will stimulate the ear to a point at which discomfort gives way to definite pain, was called the threshold of pain (C-4, C-32). Between audibility and pain a pressure increase of one million times is involved which shows the extremely wide range of sound pressure to which the ear responds. The curves of the threshold of audibility and of the threshold of pain, as functions of frequency, enclose the auditory sensation area of the human ear and are shown, after Robinson and Dadson (1956), in Figure C.1. In this figure the frequency (in cps) is shown along the horizontal axis; the values of sound levels (in dB-s) are indicated along the vertical axis; plotted against these two variables are curves of equal loudness (GB-52, C-1). It is noticeable that the ear's sensitivity varies remarkably for sounds of different frequencies. Looking, for example, at the curve of threshold of audibility, it will be seen that at 1000 cps a minimum sound pressure level of about

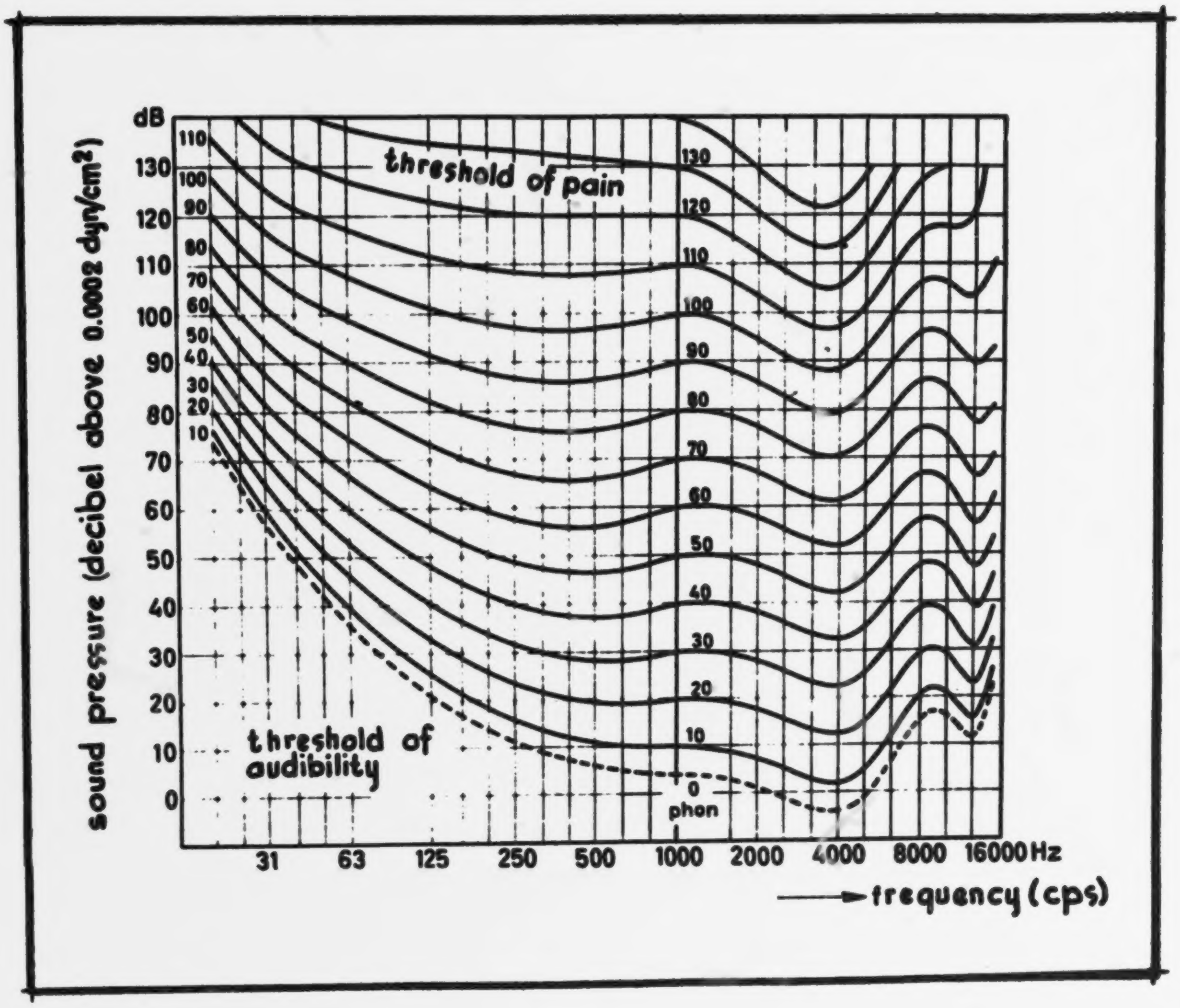


Figure C.1. The Robinson-Dadson equal loudness level curves showing the region of auditory sensation area enclosed by the curves defining the threshold of audibility and the threshold of pain as functions of frequency.

4 dB is necessary to be barely perceived by the ear, while at 50 cps the ear will not respond to any sound unless its pressure reaches a minimum level of about 41 dB. To a certain degree we are deaf to low frequency sounds. The reduced sensitivity of our ears in the lower frequency range is most fortunate. It releaves us of being unnecessarily annoyed by low frequency noises continuously originating from our atmospheric environment and also from certain physiological functions of the human body (GB-52). On the other hand it is propitious that the ear is more sensitive to sounds in the frequency range between about 400 and 5000 cps which are essential for speech intelligibility (C-1) and for the full enjoyment of music.

The restricted sensitivity of the human ear in the lower frequency range applies to sounds of not too loud nature only because to sounds of a higher sound pressure level the ear is almost equally sensitive at all frequencies.

Figure C.1 also illustrates that sounds of the same pressure but of different frequencies will not be judged by the ear as equally loud. If two tones, e.g., 125 cps and 4000 cps, both have a sound pressure level of 30 dB, the former will be judged as 16 phon, while the latter as 37 phon. The sound pressure level of the 125 cps tone must be 45 dB if it is to evoke the same loudness sensation as the 4000 cps tone of 30 dB sound pressure level. In other words, the ear is less sensitive to the low frequency 125 cps than to the high frequency 4000 cps sound.

On the other hand, a 4000 cps tone having a sound pressure level of only 20 dB sounds as loud as a 63 cps tone having a sound pressure level of 50 dB. Both will have a loudness level of 27 phons.

At low frequencies a given change in sound pressure level produces a much larger change in loudness level than does the same change at higher frequencies (C-1).

It must be noted that at 1000 cps the sound pressure levels in dB are the same as the loudness levels in phons, e.g., a sound pressure level of 80 dB has a loudness of 80 phons. The graph on Figure C.1 also enables us to transpose any single tone from dB-s into phons, or vice versa; e.g., a tone at 4000 cps at a sound pressure level of 70 dB will have a loudness of about 80 phons.

C.6 Timbre

It has been mentioned before that musical sounds usually do not contain a single frequency component only (as created e.g., by a tuning fork). They include several frequencies: low, medium and high frequency components; they are called complex tones.

The component of lowest frequency present in a complex tone is called the fundamental, while components of higher frequencies are called partials. If the frequencies of the partials are simple, integral multiples of the fundamental, they are called harmonics. Some musical instruments generate sounds with as many as thirty or forty harmonics in the audible frequency range. In some cases the harmonics may be more prominent than the fundamentals (C-1). For many musical sounds the pitch of the entire complex tone seems to be the same as that of the fundamental, nevertheless, the partials add distinctive qualities to the tone. It is the relative number, prominence, pitch and intensity of the harmonics or partials which contribute to the quality or timbre of the musical sounds. Timbre is that attribute of auditory sensation in terms of which a person can distinguish between sounds, similarly presented on different musical instruments, having the same pitch and loudness (C-32).

C.7 Directionality of sound sources

Although sound sources radiate sound waves in all directions, nevertheless, in a region free from reflecting surfaces the intensity of the emitted sound will be most pronounced in one direction. To put it more precisely, the radiation pattern will vary with the frequency of the emitted sound wave. This phenomenon is noticeable with the human voice, with musical instruments, with loudspeakers and also with many noise sources (C-8, C-27).

The directionality of the human voice in a horizontal plane, visualized through the mouth, is shown in Figure C.2. It illustrates that the radiation of high frequency speech sounds is more pronounced along the longitudinal axis, while the distribution of the medium (and also low) frequencies is more uniform in all directions. This can be particularly observed in excessively wide Auditoria where the high frequency components of speech are not as efficiently radiated to the side seats of the front rows as to the center seats, resulting in a pronounced loss of intelligibility at these side seats. Experience has shown, however, that in the radiation pattern of the human voice the frequency discrimination is negligible over a total angle of 90° in the forward direction.

C.8 Masking

It is well known that while even a subdued voice will be understandable in a quiet room, it will be extremely difficult to understand even a raised voice above the roar of an airplane engine. This drowning out, or masking, occurs because the auditory nerves in the ear are unable to carry all the impulses to the brain at one time (C-4).

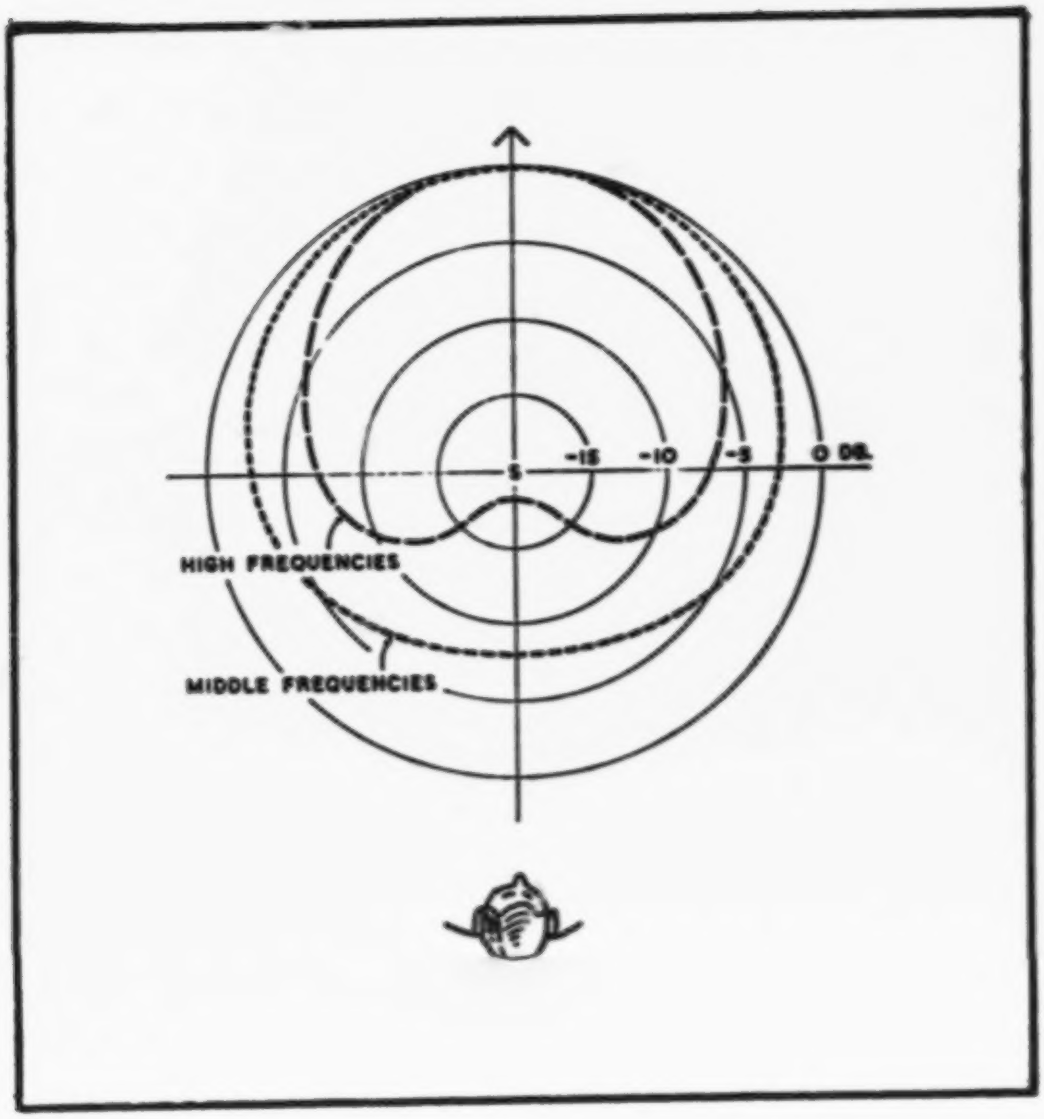


Figure C.2. Directionality of the human voice in a horizontal plane visualized through the mouth.

Masking is a frequent phenomenon in Auditoria of inadequate acoustical design when undesired noise makes it difficult or impossible to hear and understand or appreciate the desired sound. According to the standard definition, masking is the process by which the threshold of audibility for one sound, e.g., speech in an Auditorium, is raised by the presence of another (masking) sound, e.g., street noise or ventilating noise.

Low frequency sounds produce a considerable masking effect upon high frequency sounds, particularly if these low frequency sounds are significantly loud. Excessive low frequency noises constitute, therefore, a serious source of interference for listening to speech or music, since they will mask wanted sounds of the entire audio-frequency range. The elimination of these low frequency noises is an important goal in the acoustical design of Auditoria.

High frequency sounds create only a limited masking upon low frequency sounds. The masking effect is most pronounced when the masking sound has almost the same frequency as the masked sound.

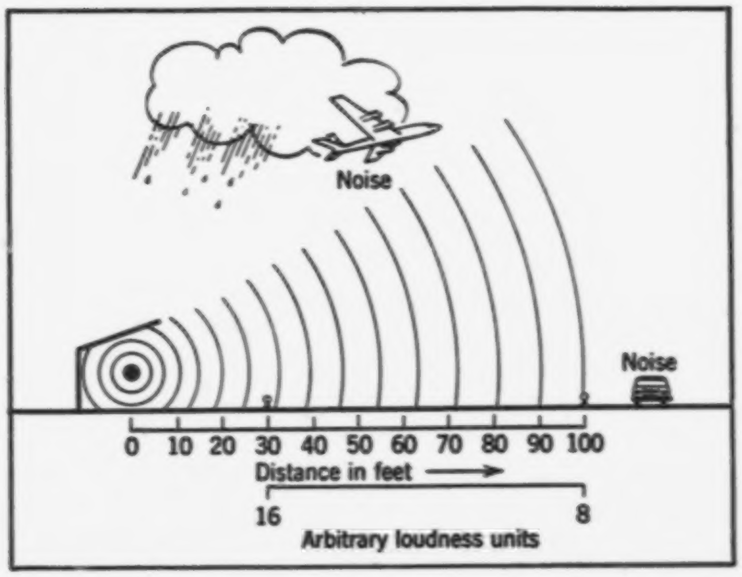
C.9 Sound and distance. Propagation of sound in the open air

In a free field (free from reflecting surfaces) a sound wave travels outward from its source in a spherical wave front, consequently, its energy will be spread over a continuously extending surface. Since the area of a sphere is proportional to the square of its radius, it follows that the intensity of sound at any point is inversely proportional to the square of the distance from the source to that point (C-4, C-5). This is known as the inverse square law in architectural acoustics (C-9, C-14, C-21, C-24).

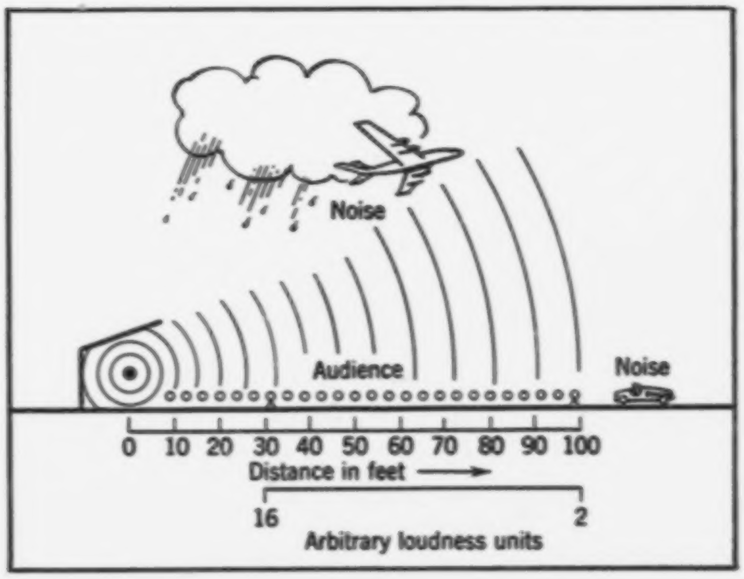
Where there are no reflecting surfaces the reduction of the intensity of sound can be regarded to be 6 dB every time the distance from the source is doubled (C-4, C-28, GB-53).

If it is essential to preserve the intensity of sound in the open air (e.g., in the case of Open-Air Theaters), its rapid attenuation can be counterbalanced by the application of sound reflectors around the sound source. Properly located and efficiently detailed sound reflectors will create a remarkable increase in sound level over the audience area. The increased absorbing effect of the audience itself and the masking effect of the background noise (a mixture of all sources of interfering interior and exterior noises) will be compensated to some extent by sloping the audience area upwards and by shielding the affected area against exterior noises. These conditions of improved acoustics in an Open-Air Theater are illustrated in Figure C.3.

Rapid attenuation of sound level in the open air can be reduced by the application of sound reflectors close to the sound source.


Noise
Noise
0 10 20 30 40 50 60 70 80 90 100
Distance in feet ⟶
16
8
Arbitrary loudness units

Sound from an orchestra shell in an open field with horizontally seated audience. The loudness of sound decreases rapidly as it travels over the audience.


Noise
Audience
Noise
0 10 20 30 40 50 60 70 80 90 100
Distance in feet ⟶
16
2
Arbitrary loudness units

Sound from an orchestra shell in an open field with audience on raked seats. The loudness of sound at the rear of the audience is enhanced by sloping the seating upwards, and by shielding the affected area against exterior noise.

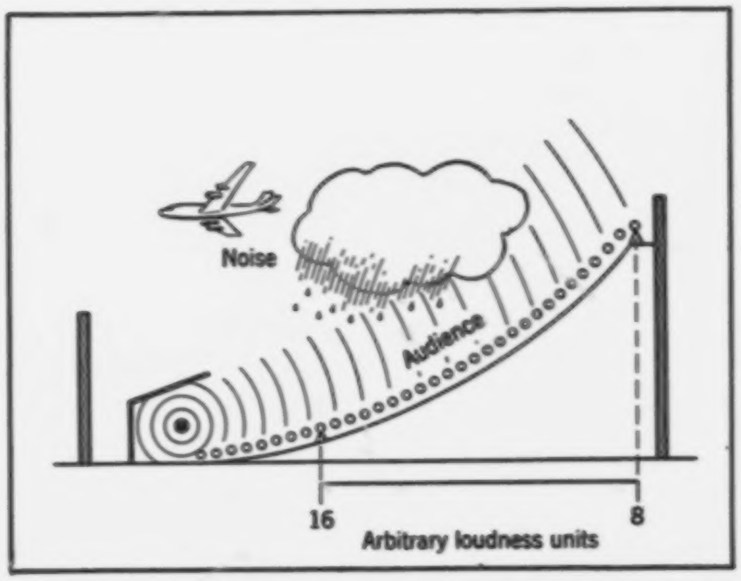

Noise
Audience
16
8
Arbitrary loudness units

Figure C.3. Acoustically improved listening conditions in an Open-Air Theater. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

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relative to Section C, "Properties of Sound"

(See list of abbreviations on page 1)

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PART II.
ROOM ACOUSTICS

Section D. Acoustical Phenomena in an Enclosed Space

D.1 Sound reflection
D.2 Diffraction
D.3 Sound absorption. Absorption coefficient
D.4 Diffusion
D.5 Growth and decay of sound in a room. Reverberation time
D.6 Room resonance. Normal modes
References

It was mentioned in the preceding Section that in a free field the energy of sound waves, traveling outwards from their original source in a continuously extending spherical wave front, will gradually attenuate as the distance from their source increases.

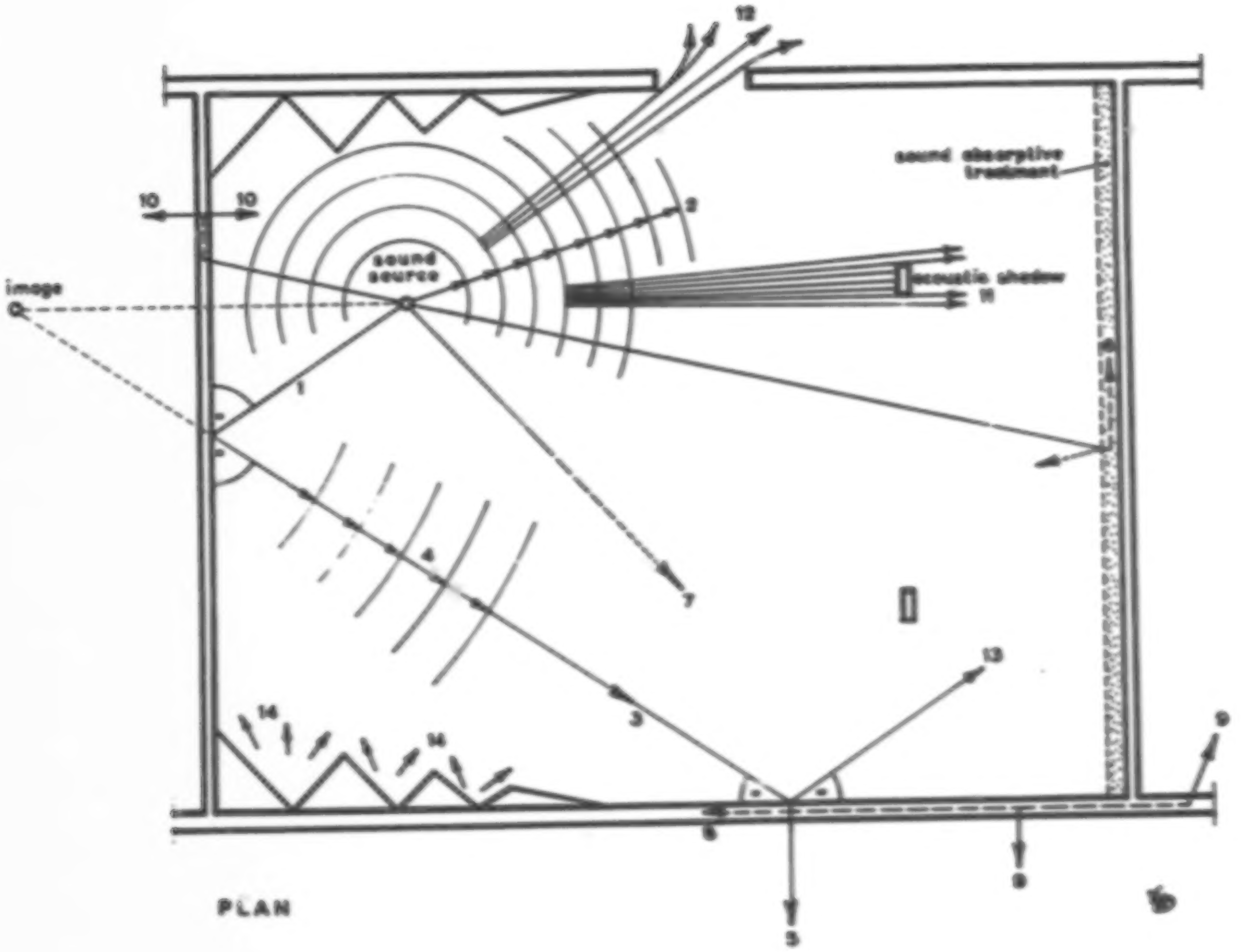
In architectural design, however, room acoustical problems of enclosed spaces are mostly encountered. The propagation and behaviour of sound waves in enclosed spaces is more complex than in the open air and it will certainly require experience and imagination to follow the rather complicated path of even a single sound wave inside a room.

The study of the behaviour of sound waves in a room can be simplified if we substitute the outwardly spreading layers of compression and rarefaction with imaginary sound rays, perpendicular to the advancing wave front, traveling in straight lines in every direction of the space, quite similarly to beams of light in optics. This approach in architectural acoustics, that likens the behaviour of sound waves to those of light rays, is called geometric acoustics. Figure D.1 illustrates that when sound waves strike the enclosures of a room, part of their energy will be reflected, part of it will be absorbed, and part of it will be transmitted through the structure into other rooms of the building.

The behaviour of sound in enclosed spaces will be discussed in this Section (D-1, D-2, D-3, D-8, D-28).

D.1 Sound reflection

Hard, rigid and flat surfaces, such as concrete, plaster, glass, etc., will reflect almost all incident sound energy striking these surfaces. This phenomenon of sound reflection is quite similar to the well known reflection of light (D-1), since,(a) the incident and the reflected sound rays lie in the


12
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sound source
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sound absorptive treatment
acoustic shadow
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Figure D.1. The behaviour of sound in an enclosed space.

1 incident sound
2 direct wave front
3 reflected sound
4 reflected wave front
5 sound transmitted through enclosure
6 sound absorbed at wall surface
7 sound absorbed in the air
8 sound energy dissipated within the structure
9 structure-borne sound conducted to other parts of the building
10 sound radiated by flexural vibration of the enclosure
11 acoustic shadow
12 diffraction of sound through opening
13 multiple sound reflection contributing to reverberation
14 diffused sound due to surface irregularities

same plane, and (b) the angle of the incident sound wave will equal the angle of reflection (law of reflection). In Figure D.1 sound rays 1 and 3 illustrate the phenomenon of sound reflection. It must be remembered, however, that the wavelengths of sound waves are much larger than those of the light rays, and the law of sound reflection is valid only if the wavelengths of the sound waves are small compared to the dimensions of the reflecting surfaces. This means that the application of this law must be very critically considered for low frequency sounds and for small rooms (GB-52).

Concave reflecting surfaces will tend to concentrate while convex surfaces will disperse the reflected sound waves in the rooms (D-1, D-38, GB-53).

In medium and large size Auditoria hearing conditions can be considerably improved by the application of large and suitably located sound reflectors (further discussed in Section F).

D.2 Diffraction

Diffraction is the acoustical phenomenon which causes the sound waves to be bent and scattered around obstacles (corners, piers, columns, walls, beams, etc.), so that these elements do not cast a complete acoustic shadow as shown at area 11 of Figure D.1, but wave "fringes" will develop around the obstacles, as shown at area 12 of the same Figure (D-1, D-38, GB-53). Diffraction, i.e., the bending and scattering of sound waves around obstacles, is more pronounced for low frequency sounds than for high frequency sounds. This repeatedly proves that the laws of geometric acoustics are inadequate to predict precisely the behaviour of sound in enclosed spaces because the obstacles usually encountered in room acoustics are too small compared to the wavelengths of the audible sound waves. Geometric acoustics, a useful approach in the problems related to high frequency sounds, is hardly applicable to frequencies below 250 cps (D-73), in other words, low frequency sounds (of long wavelengths) will not respect the laws of geometric acoustics if they encounter architectural elements of small dimensions; in particular, (a) they will not travel in "rectilinear" directions through an opening, and (b) they will not diffract, or be scattered by small scale architectural elements such as beams, coffers, pilasters, cornices, etc., of small dimensions (D-38, D-73).

Experience gives ample evidence that deep galleries cast an acoustic shadow on the audience underneath, causing a noticeable loss in the high frequency sounds (with short wavelengths) which do not bend around the protruding balcony edge. This condition creates poor hearing conditions under the balcony. It is the diffraction, however, that lessens this acoustical defect, but only at the lower region of the audio-frequency range.

D.3 Sound absorption. Absorption coefficient

It is well known that soft, porous materials, fabric furnishings and people absorb a considerable portion of the sound waves bouncing on them, in other words, they are sound absorbers. By definition, sound absorption is the change of sound energy into some other form, usually heat, in passing through a material or on striking a surface (C-32). The amount of heat produced by the conversion of sound energy into heat energy is extremely small.

Practically all the building materials absorb sound in some degree; however, effective sound control of buildings will require the application of materials which are efficient sound absorbents, often termed "acoustical" materials.

In the various types of Auditoria, the following elements contribute to the overall sound absorption of the room: (a) the surface treatments of the room enclosures, such as walls, floor, ceiling (see area 6 of Figure D.1); (b) room contents, such as the audience, seats, draperies, carpets, flowers, etc.; (c) the air of the room (see area 7 of Figure D.1). The various types of sound absorbing materials, properly classified, and other elements contributing to sound absorption, will be discussed later in Section E.

The efficiency of the sound absorption of a material at a specified frequency is rated by the sound absorption coefficient. By definition, the sound absorption coefficient of a surface is the fraction of incident sound energy absorbed or otherwise not reflected by the surface (C-32). It is denoted by the Greek letter alpha (α). The α value of the various materials can vary between 0 and 1; e.g., if at 500 cps an acoustical material absorbs 65 % of the incident sound energy and reflects 35 % of it, then the sound absorption coefficient of this particular material is 0.65. The sound absorption coefficient varies with the angle at which the sound wave impinges on the material and also with the frequency (D-34). Values of sound absorption coefficients at a certain frequency, published in the architectural acoustical literature, are averaged over all angles of incidence at that particular frequency (random incidence).

For practical purposes it is a standard practice to list α values at representative frequencies throughout the most important part of the audio-frequency range, i.e.,at 128, 256, 512, 1024, 2048 and 4096 cps; or at 125, 250, 500, 1000, 2000 and 4000 cps. For all practical purposes the two series of frequencies can be regarded as identical (GB-21). In the sound control calculation of acoustically sensitive rooms (such as Concert Halls, Radio and Television Studios, etc.) it is essential to consider additional α values below and above this frequency range (D-30). The sound absorption coefficient of the various building and acoustical materials will also depend on many other factors which will be dealt with in Section E.

In the architectural acoustical literature and in information sheets published by manufacturers and dealers, commercial acoustical materials are sometimes characterized by their noise reduction coefficient (abbreviated NRC) which is the arithmetic average of the sound absorption coefficients at the frequencies 250, 500, 1000 and 2000 cps, expressed to the nearest multiple of 0.05 (E-12). This value might be of some use in comparing the acoustical efficiency of standard acoustical materials to be used for simple noise reduction purposes; however, the NRC values are seldom used in acoustical calculations.

The sound absorption of a surface is measured in sabins, having the dimensions of ft^2 (in the metric system: m^2). For example, an acoustical treatment extending over an area of 160 ft^2 and having a sound absorption coefficient of $\alpha = 0.50$, has a total absorption of $S\alpha = 160 \times 0.50 = 80$ sabins. W.C. Sabine called the absorption units "open window units" because they are the equivalent in absorption to an identical area of open window, which naturally absorbs 100 % of the incident sound energy and, therefore, has an absorption coefficient of 1.0. The "open window unit" expression has been renamed "sabins" to commemorate Professor Sabine.

D.4 Diffusion

If the sound pressure is the same in all parts of an Auditorium and it is probable that sound waves are traveling in all directions, the sound field in such a room is said to be homogeneous, in other words, sound diffusion prevails in the room. Adequate sound diffusion is an important acoustical characteristic of certain types of Auditoria (Concert Halls, Radio and Recording Studios, Music Rooms) because it promotes a uniform distribution of sound, it accentuates the natural qualities of speech and music, and prevents the rise of various acoustical defects (D-21, D-41, D-44, D-46, D-58, GB-21).

Diffusion of sound can be created in several ways: (a) by the generous application of surface irregularities and scattering elements; such as, pilasters, piers, exposed beams, coffered ceilings, serrated enclosures, etc.; (b) by the alternate application of sound reflective and sound absorptive surface treatments; and (c) by the irregular and random distribution of the sound absorptive treatments. It must be remembered again, that the overall dimensions of the surface protrusions and of the patches of absorptive treatments must be comparable to the wavelength of every soundwave within the entire audio-frequency range. The projections of the surface irregularities must reach at least 1/7 of the wavelengths of those sound waves which have to be diffused (D-1, D-11, D-18, D-56, D-60, D-61, D-63, D-67).

D.5 Growth and decay of sound in a room. Reverberation time

When a steady sound is generated in a room the sound pressure will gradually build up and it will take some time, in most rooms about 1 second, until it reaches its steady state value (D-1). If the sound field is diffuse in the room, i.e., the sound energy is uniformly spread over all the room, and sound waves are traveling in all directions, then, the steady state sound pressure level will be directly proportional to the acoustic power output of the source and inversely proportional to the total absorption of the room (GB-32).

Similarly, when the source of the sound has stopped, a noticeable time will elapse before the sound will die away (decay) to inaudibility. This prolongation of sound as a result of successive reflections in an enclosed space after the source of sound is "turned off", is called reverberation (C-32). Reverberation has a distinct effect on the hearing conditions of Auditoria because its presence will modify the perception of transient sounds (i.e., those having sudden starting or stopping characteristics). It is an important goal in the reverberation control of Auditoria that transient sounds of speech and music be most favorably preserved to secure the highest intelligibility of speech and the full enjoyment of music. Speech transients (consonant sounds and syllables) follow one another at the rapid rate of about 10 to 12 per second. The rate of succession of musical sounds widely varies depending on the type of music but can be as high as 20 notes a second. It is, therefore, obvious that excessive reverberation will create an acoustical condition under which transients preceding the ones upon which momentary attention is focussed remain perceptible, masking and overlapping subsequent speech or musical sounds (D-1, D-25, D-33, GB-21).

The unfavorable (often disastrous) acoustical conditions prevailing in highly reverberant Auditoria (mainly Churches, such as the Cathedrals of Cologne and Milan, St. Peter's in Rome, etc.) are well known to everybody. Speech intelligibility is practically non-existent in those Auditoria (D-29).

The importance of reverberation control in the acoustical design of Auditoria has necessitated the introduction of a relevant standard of measure: the reverberation time (abbreviated: R.T. in subsequent discussions). This is the time for the sound pressure level in a room to decrease 60 dB after the source of the sound is stopped (C-32).

As mentioned before, W.C. Sabine of Harvard University was the first who established quantitative relationship between R.T., the volume of the room and the total amount of absorption applied along the enclosures of the room (B-1, B-2). The Sabine formula for the calculation of R.T. is:

$$R.T. = \frac{0.049\ V}{A}$$

where R.T. is the reverberation time in seconds,
0.049 is a constant,
V is the volume of the room in ft^3, and
A is the total absorption in ft^2 units.

The absorption of a surface is found by multiplying its area by its absorption coefficient (α), and the total absorption "A" is obtained by the addition of these products with the inclusion of the absorption provided by the audience and other room contents (seats, furnishings, etc.). Thus

$$A = S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 \quad \ldots S_n\alpha_n$$

where $S_1 \ldots S_n$ are the individual areas in ft^2, and
$\alpha_1 \ldots \alpha_n$ are their respective absorption coefficients.

In simple cases the Sabine formula is sufficiently accurate to give a quick idea as to the R.T. of a room, however, for more precise calculations the following improved formula is used, developed by Jäger, Norris, and Eyring (D-4, D-5, D-26, D-35, D-48, D-73):

$$R.T. = \frac{0.049\ V}{S\left[-2.30 \log_{10} (1-\bar{\alpha})\right] + xV}$$

where S is the total surface area of the room in ft^2,
$\bar{\alpha}$ is the average absorption coefficient of all the room surfaces, and
x is the air absorption coefficient dependent on the temperature and humidity of the air, and also on the frequency of the sound.

Since the air absorption is negligible in the lower frequency range, the term xV is considered at the higher frequencies only (at 1000 cps and above). Table D.1 gives values of the air absorption xV in ft^2 units, for a volume of 1000 ft^3, and for a room temperature of 70° F (E-122).

Table D.1. Air absorption xV, in ft^2 units, for a volume of 1000 ft^3, and for a room temperature of 70° F.

Frequency cps	Relative humidity, %					
	30	40	50	60	70	80
1000	1	1	1	1	1	1
2000	3.5	2.5	2.5	2	2	2
4000	12	9	7	6	5	5
6000	28	21	16	13	11	10
8000	47	35	28	23	20	17

The average absorption coefficient $\bar{\alpha}$ can be obtained from the following equation:

$$\bar{\alpha} = \frac{A}{S}$$

where A is the total absorption in ft^2 units, and S is the total surface area of the room in ft^2.

Whenever the average absorption coefficient $\bar{\alpha}$ is small, e.g., 0.10 or less, the term $\left[-2.30 \log_{10} (1-\bar{\alpha})\right]$ is numerically very close to $\bar{\alpha}$, therefore, for values of $\bar{\alpha}$ less than 0.10 the following simplified formula can be used:

$$R.T. = \frac{0.049\ V}{A + xV}$$

When $\bar{\alpha}$ is more than 0.10, the more complete formula should be used for the calculation of the R.T. in which values of $\left[-2.30 \log_{10} (1-\bar{\alpha})\right]$ for given values of $\bar{\alpha}$ can be obtained from Table D.2 (D-73).

Table D.2. Values of $\left[-2.30 \log_{10} (1-\bar{\alpha})\right]$ for given values of $\bar{\alpha}$

$\bar{\alpha}$	$-2.30 \log_{10} (1-\bar{\alpha})$	$\bar{\alpha}$	$-2.30 \log_{10} (1-\bar{\alpha})$
.01	.0100	.31	.3706
.02	.0202	.32	.3852
.03	.0304	.33	.4000
.04	.0408	.34	.4151
.05	.0513	.35	.4303
.06	.0618	.36	.4458
.07	.0725	.37	.4615
.08	.0833	.38	.4775
.09	.0942	.39	.4937
.10	.1052	.40	.5103
.11	.1164	.41	.5270
.12	.1277	.42	.5441
.13	.1391	.43	.5615
.14	.1506	.44	.5792
.15	.1623	.45	.5972
.16	.1742	.46	.6155
.17	.1861	.47	.6342
.18	.1982	.48	.6532
.19	.2105	.49	.6726
.20	.2229	.50	.6924
.21	.2355	.51	.7125
.22	.2482	.52	.7331
.23	.2611	.53	.7542
.24	.2741	.54	.7757
.25	.2874	.55	.7976
.26	.3008	.56	.8201
.27	.3144	.57	.8430
.28	.3281	.58	.8665
.29	.3421	.59	.8906
.30	.3565	.60	.9153

It must be stressed that all reverberation formulae apply only to Auditoria in which the sound is diffuse, i.e., the sound energy is evenly distributed all over the room and therefore the sound dies away in a smooth, even manner, free from disturbing fluctuations. The sound field cannot be considered as diffuse in rooms (a) which have acoustical treatments concentrated on just a single area (or very few areas), (b) which have enclosures creating reflected sound concentrations (highly reflective domes, curved and acoustically untreated walls, etc.), (c) if one room dimension is disproportionately different from the other two dimensions (GB-21). In reality, few Auditoria exist in which the sound field is truly diffuse. For this reason considerable discrepancy will be observed between measured and calculated R.T. values in most Auditoria. Fortunately, the achievement of a perfectly diffuse sound field in a room is not necessary either, because under completely diffuse conditions the directional characteristic of the approaching sound waves would fade away.

Since the absorption of the various materials and finishes used in the design of Auditoria varies with frequency (often very considerably), naturally the R.T. values will also vary with frequency. It is, therefore, essential to specify or calculate the R.T. for a number of representative frequencies of the audiofrequency range. The number of these representative frequencies will depend on the importance attached to acoustical considerations. If reference is made to a R.T. value without referring to any particular frequency, this is generally agreed to be the R.T. at 512 (or 500) cps (GB-21).

Figure D.2 illustrates reverberation time diagrams of various well known Auditoria.

Excessively long R.T. can be easily detected in an existing Auditorium by simply listening, because speech will be probably unintelligible and music unenjoyable in such a room. However, if the acoustical correction of such an existing Auditorium is inevitable, the correct steps to be taken cannot be based on listening experience, i.e., subjective judgement alone (D-65). Precise acoustical measurements will have to be conducted in such cases to establish the amount of acoustical treatment that is necessary in the room (D-17, D-53).

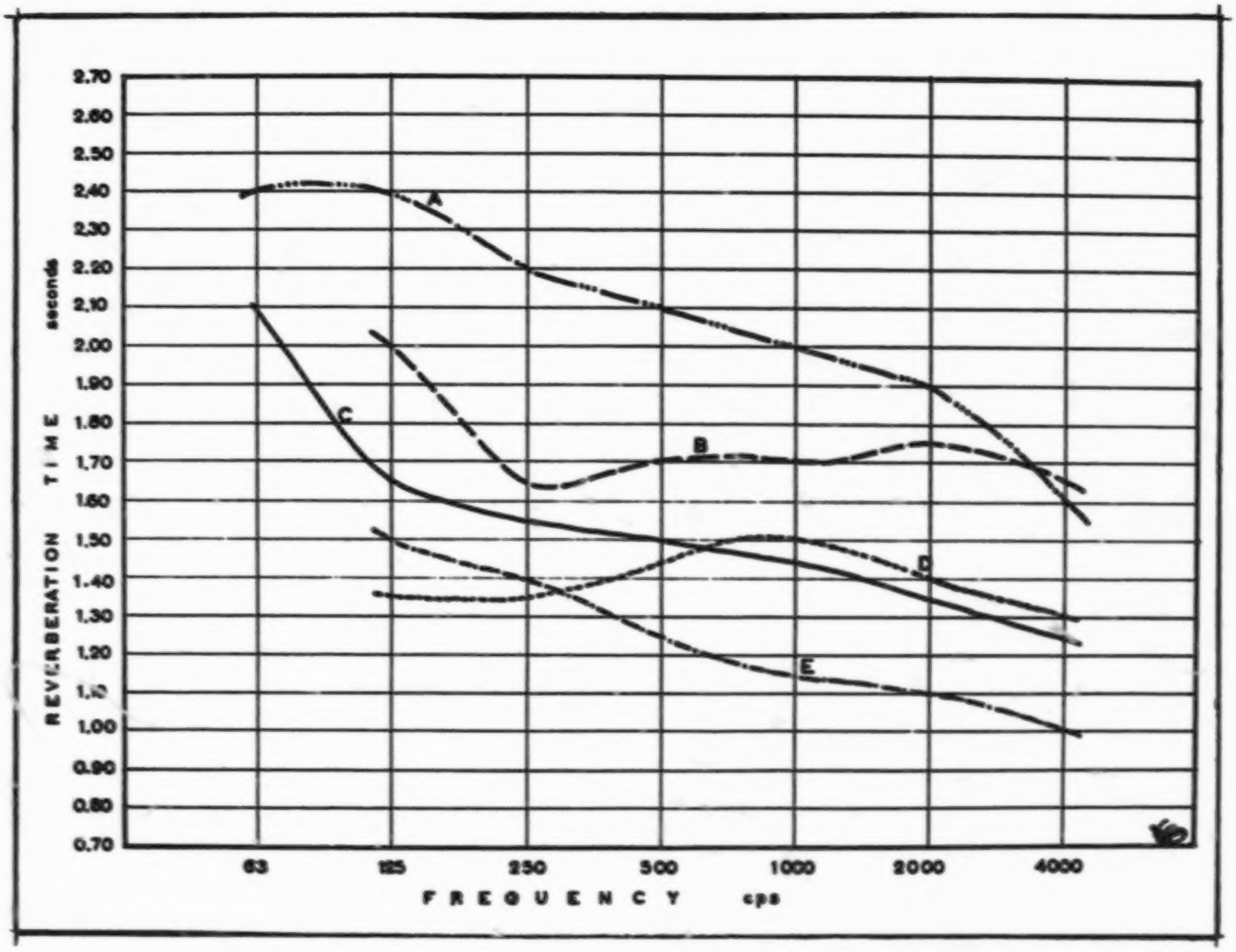

Figure D.2. Reverberation diagrams of various outstanding Auditoria. A : Musikvereinssaal, Vienna (volume= 530,000 ft^3, audience = 1680); B : Beethovenhalle, Bonn (volume = 555,000 ft^3, audience = 1407); C : Kresge Auditorium, Cambridge, Mass. (volume = 354,000 ft^3, audience = 1238); D : Royal Festival Hall, London, England (volume = 775,000 ft^3, audience = 3000); E : Teatro alla Scala, Milan (volume = 397,000 ft^3, audience = 2689).

D.6 Room resonance. Normal modes

If water is poured into a jar, it will create a gurgling tone, the frequency of which will gradually increase as the amount of water in the jar increases. The jar resonates at certain frequencies, similar to a bathroom which, by its own resonance, often encourages the vocal ambitions of home singers. It appears that an enclosed room with sound reflective interior surfaces will accentuate certain frequencies called the normal modes of vibration of the room (D-1, D-9, D-19, D-31).

Rooms, depending on their shapes and dimensions, will have an extremely large number of normal modes (also called resonant frequencies or eigentones of the room). When a complex sound is produced in a room, it will excite the room modes nearest in frequency to the components of the original sound. If only a few prominent modes are excited, there may be undesirable fluctuations during the growth and decay of sound (D-20).

The deleterious effect of too few modes is particularly noticeable (a) at the lower frequency range where these modes are unequally distributed and therefore will stand out more strikingly, and (b) in small and medium sized rooms of comparable dimensions to the wavelengths of the audible low frequency sounds (D-13, D-23, D-47, D-49).

The number of the normal modes of vibration cannot be altered within the same room but their distribution can be rendered more uniform and so their detrimental contribution can be reduced (a) by acoustically favorable room proportions (discussed in Section F), (b) by irregularly laid out room enclosures, (c) by abundantly applied surface irregularities of large dimensions, and (d) by the uniform distribution of absorptive treatments along the boundary enclosures (D-1,D-44).

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relative to Section D, "Acoustical Phenomena in an Enclosed Space"

(See list of abbreviations on page 1)

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Section E. Sound Absorbing Materials and Constructions

- E.1 Porous materials
    - E.1.1 Prefabricated acoustical units
    - E.1.2 Acoustic plasters and sprayed-on materials
    - E.1.3 Acoustical blankets
- E.2 Non-perforated panel or membrane absorbers
- E.3 Cavity (or Helmholtz) resonators
    - E.3.1 Individual cavity resonators
    - E.3.2 Perforated panel resonators
    - E.3.3 Slit resonator absorbers
- E.4 Space absorbers
- E.5 Variable absorbers
- E.6 Air absorption
- E.7 Mounting and distribution of acoustic finishes
- E.8 The choice of sound absorbing materials
- E.9 Measurement of sound absorption
    - E.9.1 Tube method
    - E.9.2 Reverberation chamber method
- E.10 Classification of materials and room contents contributing to sound absorption
- References

All building materials and finishes used in the construction of Auditoria have the capability of absorbing sound in some degree. In this Section, however, only those proprietary or custom designed building materials and room contents will be considered which will contribute significantly to the reverberation control of Auditoria, or to the noise reduction of rooms (E-1, E-5).

Although, under special conditions, many of the sound absorptive building materials and acoustical materials are also successfully used in sound insulating constructions (to be discussed in Section M), yet sound absorption should not be confused with sound insulation.

On striking any surface, sound will be either reflected or absorbed; the sound energy which is absorbed by the absorbing material will be partially converted into heat energy, but mostly transmitted to the other side of the absorbing material, unless such transmission is restrained by a backing of a hard, impervious and heavy barrier. In other words,a good sound absorber is an efficient sound transmitter and,consequently, an inefficient sound insulator. An effective sound insulating enclosure, on the other hand, will prevent the transmission of sound from its one side to the other.

Sound absorbing materials and constructions used in the acoustical design of Auditoria or for the sound control of noisy rooms can be classified as: (1) porous materials, (2) membrane absorbers, and (3) cavity resonators.

Acoustical materials from any of these classifications,and also the combinations of these materials (as individually designed acoustical treatments),can be mounted on the room enclosures or suspended in the air as space absorbers.

This Section describes the most frequently used acoustical materials and also the various room contents which contribute to the overall sound absorption in rooms. It reviews their acoustical properties and their methods of installation; it emphasizes the requirements that must be met in the choice of acoustical finishes and gives some information on the measurement of sound absorption. At the end of the Section tables list the sound absorption coefficients of various building materials, acoustical finishes and room contents which contribute to the sound absorption in rooms.

E.1 Porous materials

The basic acoustical characteristic of all porous materials (such as fibreboards, mineral wools, insulation blankets, etc.) is a cellular network of minute interlocking pores which will convert the incident sound energy into heat energy by the frictional and viscous resistance within these pores and by vibration of their small fibres (E-3). The fraction of the incident sound, thus converted into heat, will be absorbed, while the remainder, reduced in energy, will be reflected from the surface of the material (E-188). Cellular materials with closed and non-interlocking cells, such as foamed resins, cellular rubbers, foamglass, etc. are ineffective as porous absorbents (E-9, E-11, E-26, E-31, E-32, E-62, E-158).

Figure E.1 illustrates typical characteristics of porous absorbents: (a) their sound absorption is more efficient at the high than at the low frequencies, and (b) their acoustical efficiency improves in the low frequency region with increased thickness and if spaced away from their solid backing.

Commercial porous materials can be divided into the following 3 categories: (a) prefabricated acoustical units, (b) acoustical plasters and sprayed-on materials, and (c) acoustical blankets.

E.1.1 Prefabricated acoustical units

For the convenience of those interested, these types of acoustical materials, produced in an immense quantity and wide va-

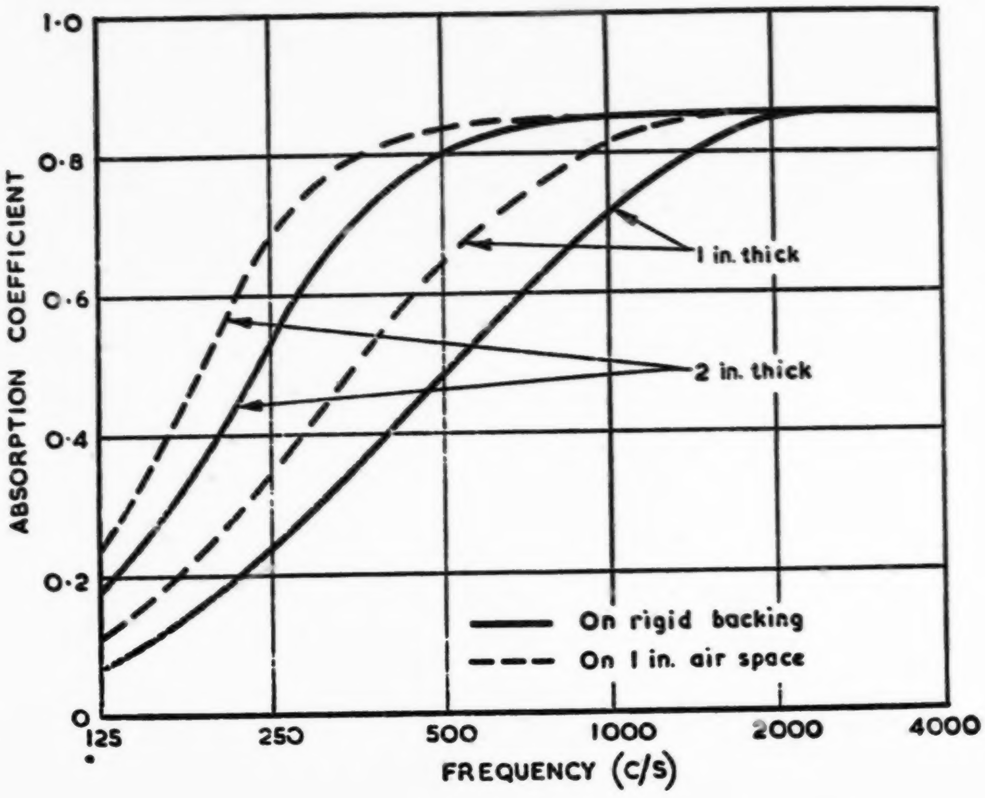


Figure E.1. Sound absorption of mineral wool slabs, 1" and 2" thick, on rigid backing, and on 1" battens. (Reprinted from Sound Absorbing Materials by E.J. Evans and E.N. Bazley, Her Majesty's Stationery Office, London, 1961).

riety by the acoustical materials industry, are described, grouped, and classified in the annual Bulletin of the Acoustical Materials Association, "Performance Data - Architectural Acoustical Materials" (E-12).

Various types of perforated, smooth, fissured or textured cellulose and mineral fibre tiles, lay-in panels, perforated metal pans with absorbent pads, etc., constitute typical, general purpose units in this group. The various catalogues distributed by representatives or agents of the acoustical materials industry, usually contain a detailed description and information on size, thickness, finish, methods of installation, acoustical efficiency, maintenance, flame resistance and other important properties of these prefabricated acoustical units. It is imperative that acoustical properties of these units, as included in the catalogues and pamphlets, should be supplied by accredited acoustical laboratories so that pertinent values of acoustical efficiencies may be compared on an equal basis (E-10).

The use of prefabricated acoustical units offer the following advantages: they possess a reliable, factory-guaranteed absorption value; their installation and maintenance is relatively easy and economic; many of them can be redecorated without causing any serious deterioration in their absorption. Their application, on the other hand, undoubtedly presents a few design problems, such as: it is difficult to conceal joints between adjacent units (E-3); their relatively soft structure is subjected to mechanical injuries if installed at lower levels of the enclosures; difficulty is usually encountered when these mass-produced units have to be aesthetically integrated into an individual architectural design (E-3, E-4, E-7, E-11, E-105).

E.1.2 Acoustical plasters and sprayed-on materials

These acoustical finishes are used mostly for noise reduction purposes and sometimes in Auditoria where the application of any other acoustical treatment would be impractical due to the curved or irregular shape of the surface.

Their acoustical efficiency will depend largely on several local job conditions, such as thickness and composition of the plaster mixture, the amount of binder, the state of the undercoat at the time of application, the manner in which the finish is applied, etc. In order to obtain the desired acoustical result, it is essential that the job be executed by competent and responsible workmen and that the manufacturers' specifications be followed strictly (E-4, E-7, E-63, E-113).

The maintenance of acoustical plasters and sprayed-on finishes (sprayed mineral fibers) certainly offers some difficulties. Redecoration may create serious deterioration of their acoustical properties unless manufacturers' pertinent instructions are fully respected (E-3).

E.1.3 Acoustical blankets

Acoustical blankets are manufactured from rockwool, glass fibres, wood fibres, hairfelt, etc. Usually installed between a wood or metal framing system, these blankets are used for acoustical purposes in varying thicknesses between about 1" and 6". Their absorption increases with thickness, particularly at the low frequencies; if space is available a considerable degree of low frequency absorption, a characteristic usually missing in other porous absorbents, can be achieved by use of a 3" to 4" thick acoustical blanket. By choice of adequate thickness, density and method of installation, acoustical blankets will supply a remarkable variety of absorption characteristics (E-3, E-9).

Since acoustical blankets do not constitute an aesthetically satisfactory acoustical finish, they are normally covered with a suitable type of perforated board, wood slats, flyscreening, etc., placed over the blankets and fastened to the framing system (discussed in paragraph E.3.2).

E.2 Non-perforated panel or membrane absorbers.

The non-perforated panels or membrane absorbers represent the second group of sound absorbing materials. Any impervious material, installed on a solid backing but separated from it by an air space, will be set to vibration when struck by sound waves (E-3, E-4, E-8, E-16, E-17, E-56, E-69, E-71, E-76). The flexural vibration of the panel absorber will then absorb a certain amount of the incident sound energy by converting it into heat energy. The theory of absorption provided by a vibrating panel is rather complicated but it is a fair approximation to assume that maximum absorption will occur in the region of the resonance frequency of the panel. This may be calculated from the formula (E-3, E-4, E-8, E-11):

$$f_{res} = \frac{170}{\sqrt{md}}$$

where f_{res} is the resonance frequency in cps,
m is the surface density in lb/ft^2, and
d is the depth of air space behind the panel in inches.

The resonance frequency is normally at the lower end of the audio-frequency range, therefore, panel absorbers are efficient as low frequency absorbers. When selected properly, panel absorbers will balance the somewhat excessive medium and high frequency absorption supplied by porous absorbers and room contents. Thus, panel absorbers will contribute efficiently to the production of a uniform reverberation characteristic over the entire audio-frequency range (E-110, E-116, E-179).

Figure E.2 illustrates the absorption-frequency characteristics of a 3/16" thick plywood panel, spaced 2" from the wall with and without porous absorbent in the air space (E-11). Maximum absorption occurs at about 150 cps and the application of porous absorber in the air space increases the absorption at the resonance frequency, broadening the otherwise narrow region of increased absorption.

Amongst various Auditorium finishes and constructions the following panel absorbers will contribute significantly to low frequency absorption: wood and hardboard panelings, gypsum boards, suspended plaster ceilings, furred out plasters, rigid plastic boards, windows, glazings, doors, wood floors and platforms, etc. Because of increased resistance against wear and abrasion, many of these non-perforated panel absorbers are often installed on the lower parts of walls, thereby providing a suitable finish for the dado (E-2, E-10, E-17, E-110, E-128, E-147, E-179).

Porous materials, spaced away from their solid backing will also act as vibrating panel absorbers, favorably contributing to absorption at low frequencies.

E.3 Cavity (or Helmholtz) resonators

The cavity or Helmholtz resonators constitute the third and last group of sound absorbents. They consist of an enclosed body of air confined within rigid walls and connected by a narrow opening (called the neck) with the surrounding space in which the sound waves travel (E-3, E-4, E-99, E-175).

A cavity resonator of this type will absorb maximum sound energy in the region of its resonance frequency.

An empty jar or bottle, as described in paragraph D.6, also acts as a cavity resonator; however, its maximum absorption is confined to a very narrow frequency band, i.e.,it is extremely

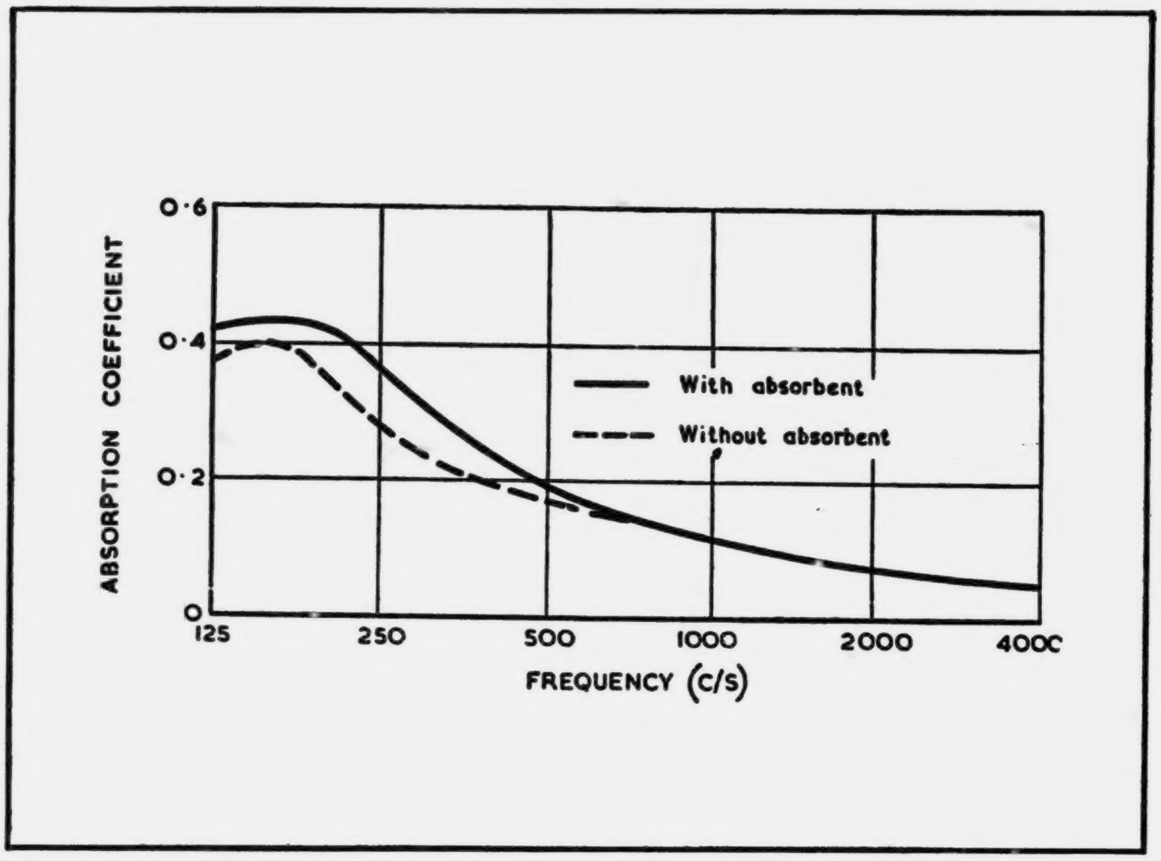


Figure E.2. Absorption - frequency characteristics of 3/16" plywood panels spaced 2" from the wall, with and without porous absorbent in the air space. (Reprinted from Sound Absorbing Materials by E.J. Evans and E.N. Bazley, Her Majesty's Stationery Office, London, 1961).

selective in its absorption, as illustrated in Figure E.3 (E-8).

Cavity resonators can be applied (a) as individual units, (b) as perforated panel resonators, or (c) as slit resonator panels. These will be discussed in the following paragraphs.

E.3.1 Individual cavity resonators

Individual cavity resonators were used a very long time ago in Scandinavian Churches. These resonators were made of empty clay vessels, in different sizes, so that their effective absorption (at resonance frequencies) was spread between 100 and 400 cps (E-3, E-4).

In contemporary room acoustical practice their application is restricted to particular cases when individual low frequency peaks within an exceptionally long R.T. of a room have to be reduced drastically, without affecting the R.T. at medium and high frequencies (E-8).

E.3.2 Perforated panel resonators

Perforated panels, spaced away from a solid backing, provide a widely used practical application of the cavity resonator principle. They contain a large number of necks, constituting the perforation of the panel, thus functioning as an array of cavity resonators. The perforations are usually circular, seldom slotted. The air space behind the perforation forms the undivided body of the resonator, separated into bays by horizontal and vertical elements of the framing system (E-4, E-10, E-50, E-77, E-82).

Perforated panel resonators do not provide such a selective absorption (i.e., restricted to an extremely narrow frequency band) as do single cavity resonators, particularly if an absorbent blanket is installed in the air space behind the visually exposed perforated board. If properly selected, with adequate open area (sometimes called sound transparency), the ab-

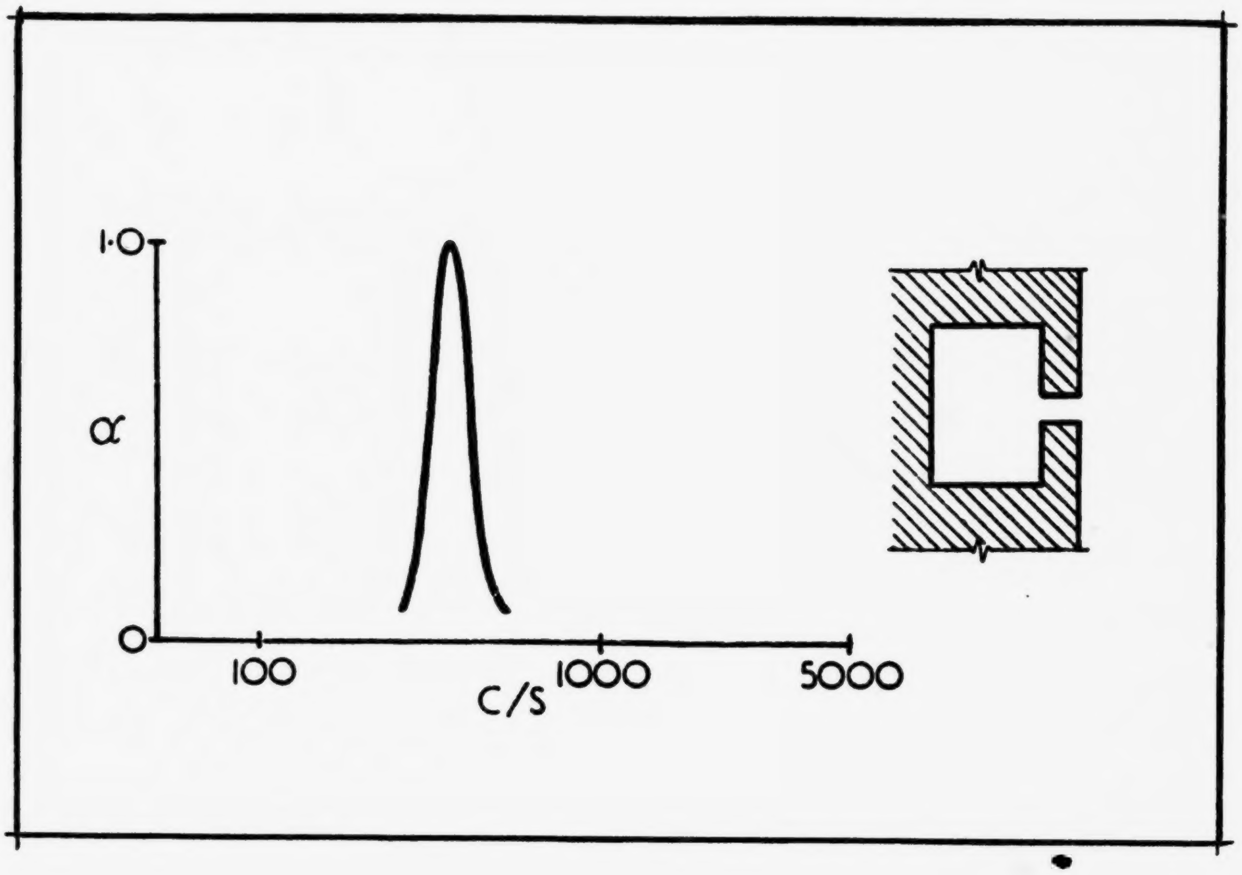


Figure E.3. Absorption characteristic of a cavity or Helmholtz resonator. (Reprinted from Acoustics, Noise and Buildings by P. H. Parkin and H. R. Humphreys, Frederick A. Praeger, New York, 1958).

sorbent blanket reduces the peak absorption but increases the overall efficiency by broadening the frequency region in which considerable absorption can be expected (E-3, E-4, E-8, E-104, E-125).

The absorption frequency curves of perforated panel resonators mostly show a maximum (peak) value in the medium region of the frequency scale with an apparent drop above 1000 cps. Therefore, if the same perforated panel treatment were to be used extensively in an Auditorium the R.T. would be unfavorably short at this peak value. A reasonably even and uniform reverberation characteristic can be provided in a room if those peak values in the absorption diagram of the perforated panel treatments are shifted to several different regions of the frequency range. This can be achieved by varying (a) the thickness of the perforated panel, (b) the size and spacing of the holes, (c) the depth of air space behind the perforated panel, (d) the type, thickness,and density of the applied acoustical blankets behind the perforated panels, and (e) the spacings between the elements of the furring system (E-3, E-4, E-11).

Various standard commercial panels or boards are available on the market in perforated form, suitable for application as perforated panel absorbers; such as, cement asbestos sheets (Transite panels), hardboard (Masonite), plain and corrugated metal (steel, aluminum, etc.) sheets, rigid plastic sheets, wood and plywood panels, reinforced fiberglas panels, plastic coated steel sheets, etc.

Surface treatment of the exposed perforated panels must be carried out in a manner such that the holes are not clogged by paint.

Figure E.4 illustrates examples of perforated panel resonators applied as acoustical treatments in various Auditoria.

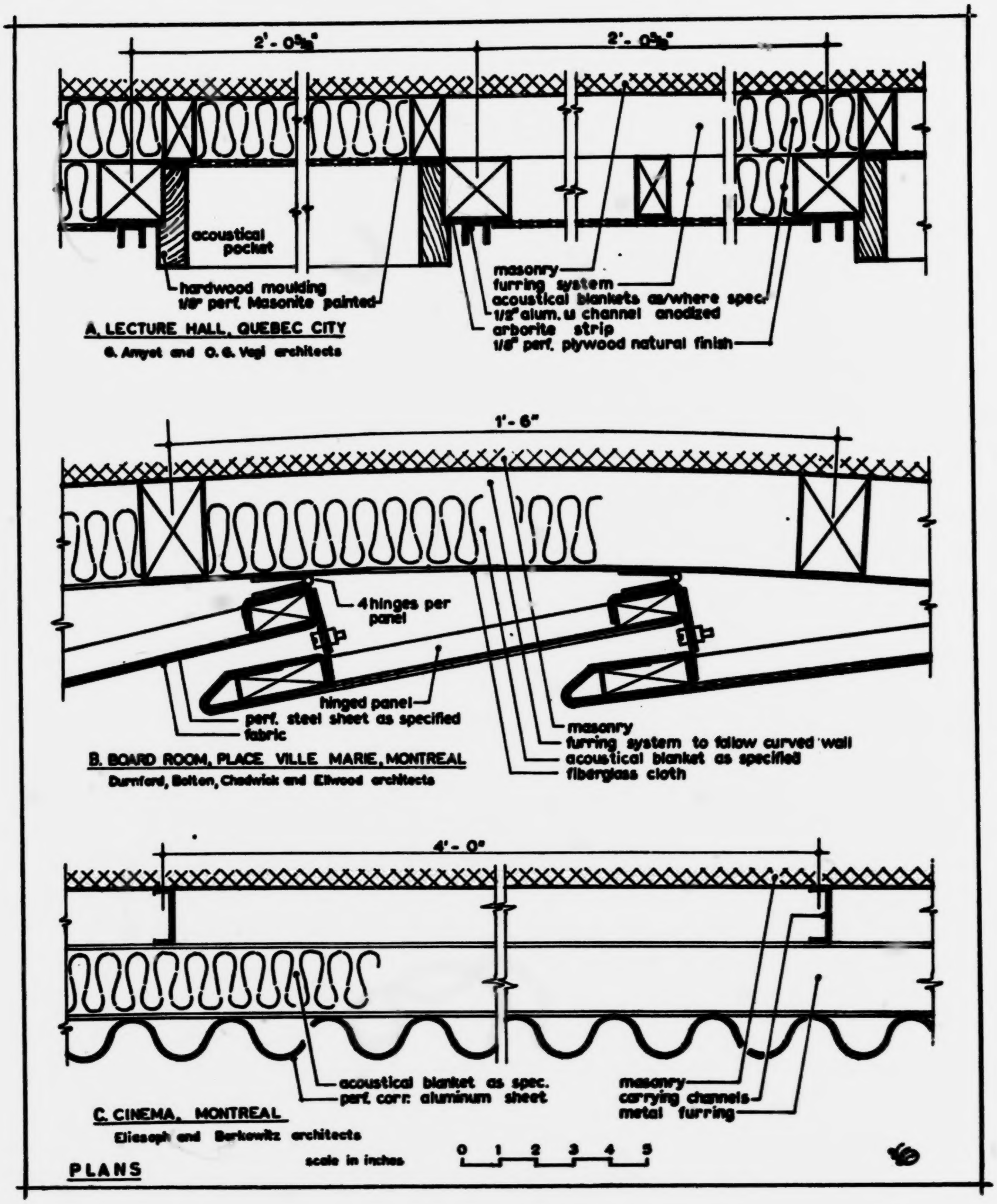

2'- 0⅝"
2'- 0⅝"
acoustical pocket
hardwood moulding
1/8" perf. Masonite painted
A. LECTURE HALL, QUEBEC CITY
G. Amyot and O. G. Vagi architects
masonry
furring system
acoustical blankets as/where spec.
1/2" alum. u channel anodized
arborite strip
1/8" perf. plywood natural finish
1'- 6"
4 hinges per panel
hinged panel
perf. steel sheet as specified
fabric
B. BOARD ROOM, PLACE VILLE MARIE, MONTREAL
Durnford, Bolton, Chadwick and Ellwood architects
masonry
furring system to follow curved wall
acoustical blanket as specified
fiberglass cloth
4'- 0"
acoustical blanket as spec.
perf. corr. aluminum sheet
C. CINEMA, MONTREAL
Eliesoph and Berkowitz architects
masonry
carrying channels
metal furring
PLANS
scale in inches
0 1 2 3 4 5

Figure E.4. Perforated panel resonators applied as acoustical treatments in various Auditoria, using : (A) perforated plywood panels and perforated Masonite boards, (B) perforated steel sheets, (C) perforated and corrugated aluminum panels. (L.L. Doelle, acoustical consultant to these jobs).

E.3.3 Slit resonator absorbers

Slit resonator absorbers have a series of exposed narrow, continuous openings (gaps) created by unidirectional slats of relatively small cross section, installed along the surface of this acoustical treatment. In many respects they are constructed similarly to the perforated panel resonators, in that they also have an air space behind the surface, mostly filled (partially or totally) with a suitable acoustical blanket. The area of opening (slits) should be at least 30 % of the total area to secure adequate sound transparency (E-4, E-72, E-171).

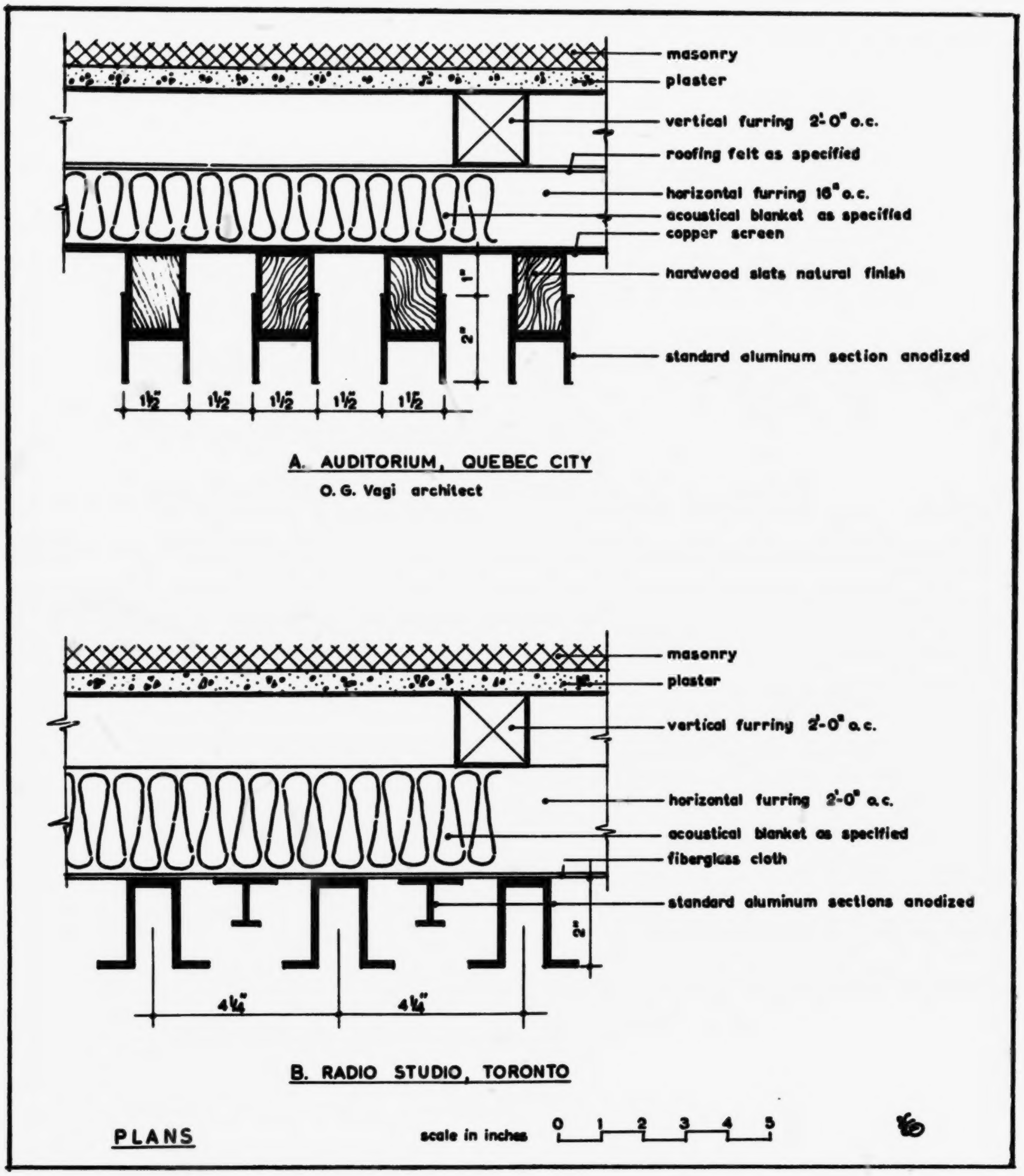
Their popularity in architectural design is due to the fact that they offer a wide choice for individual design, even though they are more expensive than the commercial and sometimes monotonous standard acoustical materials.

The characteristic feature of this acoustical treatment is a system of slats, which can be wood, steel, aluminum, plastic or other material. Figure E.5 illustrates examples of slit resonators as applied in Auditoria.

E.4 Space absorbers

When the regular boundary enclosures of an Auditorium do not provide suitable or adequate area for conventional acoustical treatments, sound absorbing objects, called space absorbers or functional absorbers, can be suspended as individual units from the ceiling (E-3, E-7, E-8, E-10, E-45, E-58, E-59).

They can be easily installed or removed, without interference with existing fixtures or equipments. Since sound waves will probably hit all sides of these absorbers, their absorption is quite powerful compared to standard, commercial acoustical materials. These advantageous features make space absorbers a particularly suitable acoustical treatment for noisy industrial areas.



A. AUDITORIUM, QUEBEC CITY

O. G. Vagi architect

B. RADIO STUDIO, TORONTO

PLANS

masonry
plaster
vertical furring 2'-0" o.c.
roofing felt as specified
horizontal furring 16" o.c.
acoustical blanket as specified
copper screen
hardwood slats natural finish
standard aluminum section anodized
1"
2"
1½"
1½"
1½"
1½"
1½"
masonry
plaster
vertical furring 2'-0" o.c.
horizontal furring 2'-0" o.c.
acoustical blanket as specified
fiberglass cloth
standard aluminum sections anodized
2"
4¼"
4¼"
scale in inches
0
1
2
3
4
5

Figure E.5. Slit resonator absorbers applied as acoustical treatments, using : (A) wood and aluminum slats, (B) aluminum slats. (L.L. Doelle, acoustical consultant to these jobs).

Space absorbers are made of perforated sheets (steel, aluminum, hardboard, etc.), in the shapes of panels, prisms, cubes, spheres, cylinders, single or double conical shells, and are generally filled or lined with sound absorbing materials such as rockwool, glasswool, etc.

The sound absorption of space absorbers is specified as the number of absorption units (sabins) supplied per individual unit. Their acoustical efficiency will depend on their spacing and will approach a constant value at wide spacings (E-7).

E.5 Variable absorbers

Since various usages of the same Auditorium, as will be seen later, would require various reverberation times, it has long been an aim of acousticians to design special sound absorbing constructions that could change the R.T., i.e.,the acoustical conditions within a room.

Several attempts have been made in the past to implement this objective, particularly in Radio Studios, where a noticeable change in the R.T. was frequently necessary. For this purpose various sliding, hinged, movable and rotatable panels have been constructed that can expose either absorptive or reflective surfaces; draperies have been installed that can spread out over walls or can be pulled back into suitable pockets, thus arbitrarily increasing or reducing the effective absorptive treatment in a room (E-3).

The construction of such variable absorbers is justified only if it will be capable of producing a reasonable (at least 20 %) change of the total absorption over a considerable region of the audio-frequency range (E-65).

Experience has given evidence that variable absorption-producing devices are practicable only for rooms which are permanently maintained and serviced by competent personnel, as might be the case for Radio or Recording Studios. It appears, however, that even in Studios the control of R.T. through conventional variable absorbers will be soon rendered obsolete due to the widely expanding application of electronically operated reverberation control.

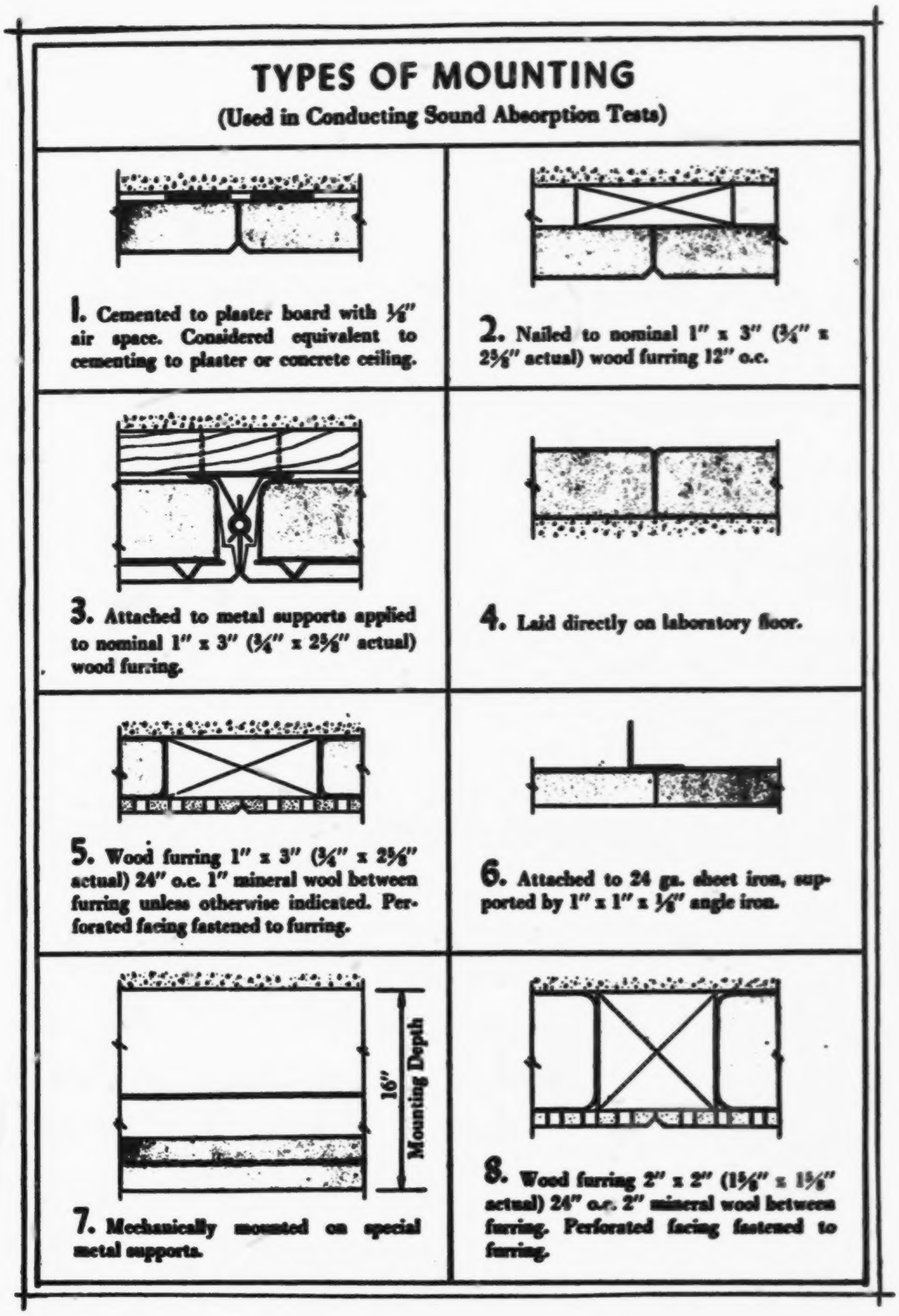
E.6 Air absorption

It has been mentioned before, that besides the various acoustical finishes and room contents, the absorption of the air (due to radiation, scattering, molecular absorption and other phenomena) will also contribute to the overall room absorption (E-3, E-11, E-14, E-122, E-132, E-185). The air absorption is affected by the temperature and humidity of the air, and represents a significant value only above 1000 cps (see Table D.1 in preceding Section).

E.7 Mounting and distribution of acoustic finishes

The sound absorption characteristic of acoustical materials should not be considered as their intrinsic property but rather as a feature largely dependent on their physical properties, installation details, and local conditions (E-3, E-7, E-21, E-62, E-84, E-96, E-97, E-114).

Since the way acoustical materials are installed will have a marked effect on their absorptive properties, comparisons between the absorption coefficients of different materials should be based on data obtained from tests conducted in an accredited laboratory and under identical mounting conditions. Typical mountings used in conducting standard sound absorption tests by the Acoustical Materials Association (335 East 45th Street, New York 17, N.Y.) are illustrated in Figure E.6 (E-12).



TYPES OF MOUNTING

(Used in Conducting Sound Absorption Tests)

1. Cemented to plaster board with ⅛" air space. Considered equivalent to cementing to plaster or concrete ceiling.

2. Nailed to nominal 1" x 3" (¾" x 2⅝" actual) wood furring 12" o.c.

3. Attached to metal supports applied to nominal 1" x 3" (¾" x 2⅝" actual) wood furring.

4. Laid directly on laboratory floor.

5. Wood furring 1" x 3" (¾" x 2⅝" actual) 24" o.c. 1" mineral wool between furring unless otherwise indicated. Perforated facing fastened to furring.

6. Attached to 24 ga. sheet iron, supported by 1" x 1" x ⅛" angle iron.

7. Mechanically mounted on special metal supports.

8. Wood furring 2" x 2" (1⅝" x 1⅝" actual) 24" o.c. 2" mineral wool between furring. Perforated facing fastened to furring.

Figure E.6. Typical mountings used in conducting standard sound absorption tests by the Acoustical Materials Association, New York. (Reprinted from Performance Data - Architectural Acoustical Materials, Acoustical Materials Association, New York, 1963).

There is no specific type of mounting that can be recommended as optimum for every installation. Various aspects have to be considered simultaneously, such as:

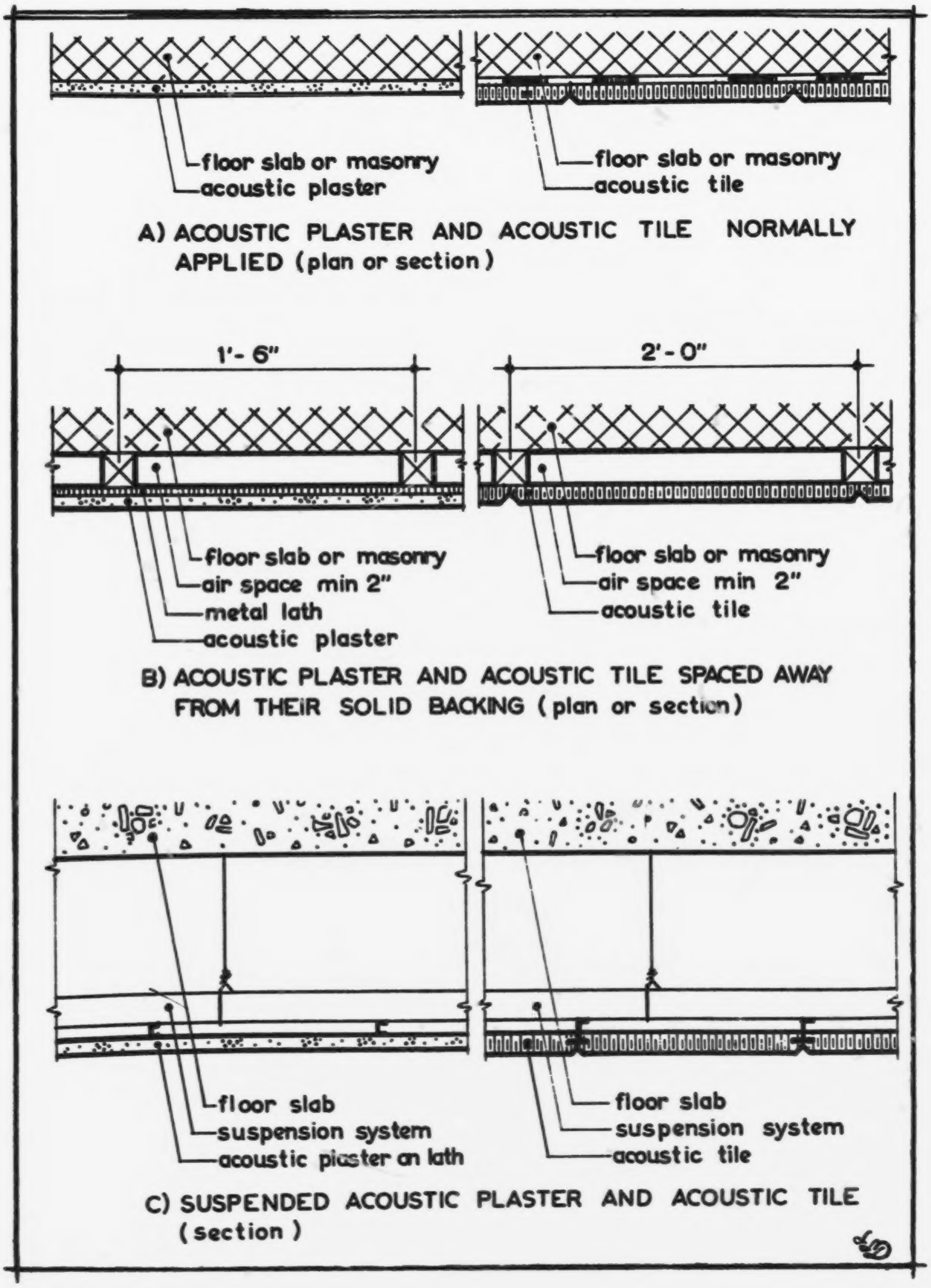
- physical properties of the acoustical material;
- strength, surface texture and location of the room enclosure on which the acoustical material will be installed;
- the space available for the treatment;
- the time required for the labor;
- probability of removal in the future;
- costs, etc.

Methods of mounting for an installation on a new construction might be basically different from those feasible in an existing building (E-3).

As mentioned before, the absorption coefficient of most acoustical materials can be increased, particularly at the low frequencies, when spaced away from their solid backing. This is illustrated for acoustic plaster and acoustic tile in Figure E.7, but the principle holds true for panel absorbers, perforated panel resonators and slit resonator absorbers alike.

The installation of acoustical treatments should always be performed by a competent contractor who is able to check whether or not conditions are suitable for a workmanlike execution of the acoustical trade. And since the acoustical work on a job is always affected by the work of many other trades, the architect should specify clearly the responsibilities of the various contractors involved.

The distribution of acoustical materials requires care in order to achieve maximum absorption and the most favorable effect on hearing conditions. The acoustical finishes should be distributed over the room enclosures as evenly as possible, partly to reduce the detrimental effect of certain normal modes of vibration and partly to provide good diffusion (E-3, E-148). The uniform distribution of acoustical finishes is, in most in-


floor slab or masonry
acoustic plaster
floor slab or masonry
acoustic tile
1'- 6"
2'- 0"
floor slab or masonry
air space min 2"
metal lath
acoustic plaster
floor slab or masonry
air space min 2"
acoustic tile
floor slab
suspension system
acoustic plaster on lath
floor slab
suspension system
acoustic tile

A) ACOUSTIC PLASTER AND ACOUSTIC TILE NORMALLY APPLIED (plan or section)

B) ACOUSTIC PLASTER AND ACOUSTIC TILE SPACED AWAY FROM THEIR SOLID BACKING (plan or section)

C) SUSPENDED ACOUSTIC PLASTER AND ACOUSTIC TILE (section)

Figure E.7. The low frequency absorption of standard acoustic plaster and acoustic tile (A) can be increased when spaced away from their solid backing (B), or used in connection with a suspension system (C).

stances, extremely difficult for several reasons: (a) the audience always constitutes an area of concentrated absorption; (b) in the interest of adequate loudness and uniform sound distribution the room enclosures close to the sound source are usually treated reflectively, therefore, the accommodation of any acoustical treatment in this area is practically impossible; and (c) the rear wall of an Auditorium (opposite the sound source) mostly forms an unbroken area of absorptive treatment in order to prevent the rise of echo or too long delayed reflections from this wall (E-3, E-4, E-25, E-40, E-44, E-108, E-186).

E.8 The choice of sound absorbing materials

Since architectural acoustical materials are supposed to combine the functions of sound absorption and interior finish, it is obvious that in the selection of acoustical finishes a number of considerations, other than acoustical, must be taken into account simultaneously (E-3, E-7, E-37, E-66, E-67, E-89, E-106, E-113, E-167, E-168, E-170, E-188).

If the main purpose is to achieve a uniform (flat) reverberation diagram over the entire audio-frequency range, those acoustical finishes have to be chosen which together will produce a uniform (not necessarily high) absorption characteristic throughout the audio-frequency range. If the application of high frequency absorbents (perforated panel resonators or slit resonator absorbers) is favored, their somewhat excessive high frequency absorption can be counterbalanced by the installation of a reasonable amount of low frequency panel absorbers. If acoustically detrimental back reflections (echoes, too long delayed corner reflections) have to be eliminated or avoided, then the dangerous reflecting surfaces must be treated with acoustical materials of highly absorptive character.

The following aspects should be examined in the selection of sound absorbing finishes or constructions (E-10, E-12, E-114, E-137, E-182):

(a) sound absorption coefficients at representative frequencies of the audio-frequency range (E-12, E-131);
(b) appearance (sizes, edges, joints, colors, textures);
(c) resistance to flame spread and fire penetration (E-92);
(d) installation cost;
(e) ease of installation (E-93);
(f) permanence (resistance to impacts, mechanical injuries and abrasion);
(g) light reflectance (E-28);
(h) maintenance, cleaning, effect of redecoration upon sound absorption, maintenance cost (E-18, E-88, E-120);
(i) job conditions (temperature, humidity during installation, readiness of backings);
(j) integration of room elements (doors, windows, lighting fixtures, grilles, radiators, etc.) into the acoustical finish;
(k) thickness;
(l) weight;
(m) moisture and condensation resistance, once the room is in use (E-14);
(n) access to suspended ceilings or furred spaces;
(o) thermal insulation value (E-47);
(p) attraction for vermin, dry rot, fungus;
(r) removability (sometimes a temporary requirement to make possible adjustments of acoustical blankets);
(s) simultaneous requirement for adequate sound insulation (E-154).

E.9 Measurement of sound absorption

Various methods for the measurement of the sound absorption coefficients of acoustical materials are widely discussed in the acoustical literature. Two of these methods are of particular interest: (1) the tube method, and (2) the reverberation chamber method (E-4, E-11, E-53, E-90, E-107).

E.9.1 Tube method

This is used to measure the sound absorption coefficients of small sized samples of acoustical materials for sound waves traveling perpendicular to the surface of the sample (normal incidence). The measurement will give an indication of the sound absorption coefficient in the frequency range of about 200 to 3000 cps (E-83).

This method is unsuitable for the general measurement of sound absorption coefficients because of its limitations; it disregards the fact that sound waves in a room will strike the sound absorbing materials at various angles, and furthermore the size and method of mounting of the test sample has no similarity whatsoever to actual job conditions. For these reasons, results obtained by the tube method should be used for theoretical work, in the development of new or in the comparison of existing acoustical materials and also for quality control (E-4, E-11, E-42, E-85, E-192, GB-52).

E.9.2 Reverberation chamber method

This method utilizes a bare chamber with a long reverberation time. A large-sized sample or several samples of a sound absorbing material are installed in the chamber, thereby reducing its R.T. The sound absorption coefficient of the absorbing material is then calculated from the decrease in the R.T. of the chamber, created by the sample of the sound absorbing material. It is essential that the sound field should be diffuse in the chamber and that sound waves should hit the test sample at all possible angles (random incidence).

The size of the test specimen may vary from 60 to 100 ft^2, depending on the individual dimensions of the reverberation chamber (E-149, E-156). The standard sample area, usually specified by the testing laboratories, can be varied within the same chamber to accommodate standard size samples of the acoustical treatment under test. The samples may be tested by placing them on the floor, on the walls or ceiling of the chamber. It is essential that the sample should be installed in a manner simulating existing or predictable field conditions (E-4, E-11, E-13, E-15, E-143, E-145, E-161, E-163, GB-52).

The test sound may consist of a frequency-modulated (warble) tone or a "white noise" which causes the sound waves to hit the test sample at a greater number of angles. Measurements are made at representative frequencies along the audio-frequency range.

The sound absorption coefficient of a sound absorbing material, measured in a reverberation chamber, should not be considered as a constant of the material because this will depend on the size of the sample, its position and distribution in the chamber, the way it is mounted and also on individual physical characteristics of the chamber itself. Therefore, values of sound absorption coefficients measured in different laboratories should be compared with caution.

For the measurement of the sound absorption coefficient of acoustical materials, contemporary testing facilities in Canada are available at the National Research Council in Ottawa (Division of Building Research). In the U.S.A. the following are considered as accredited testing laboratories: the National Bureau of Standards in Washington; the Riverbank Acoustical Laboratory in Geneva, Illinois; and the Geiger and Hamme Laboratory at the University of Michigan (E-176, E-191, E-193).

E.10 Classification of materials and room contents contributing to sound absorption

Subsequent tables of absorption coefficients, covering the most common building materials, acoustical materials and room contents, are classified into 3 groups:

(1) common building materials,

(2) acoustically efficient absorbing materials, and

(3) room contents (E-80, E-118, E-120, E-155, E-165).

The coefficients are given for six representative frequencies, i.e., for 125, 250, 500, 1000, 2000 and 4000 cps, these being the most important in general acoustical design practice. Values of absorption coefficients below and above this frequency region are of use to acoustical experts only.

Sound absorption coefficients of standard acoustical materials, generally published in manufacturers' pamphlets, are, as a rule, not included in the Tables. The inclusion of a few commercial acoustical materials does not necessarily mean that they are endorsed in any way, they merely constitute typical examples of their kind.

In the data references are made to their sources (testing authorities) as follows:

1. Acoustical Materials Association, New York (E-12).
2. V.O. Knudsen and C.M. Harris (GB-21).
3. L.L. Beranek (GB-34).
4. F. Ingerslev (GB-29).
5. P.H. Parkin and H.R. Humphreys (GB-43).
6. M. Adam (GB-44).
7. National Research Council, Ottawa.
8. Geiger and Hamme.
9. Riverbank Acoustical Laboratory.
10. Johns-Manville Research Laboratory.
11. Manufacturers' own pamphlets.

Table E.1. Sound absorption coefficients of common building materials.

Description	frequency cps						Source
	125	250	500	1000	2000	4000	
Brick, unglazed, exposed, unpainted	.03	.03	.03	.04	.05	.07	1
same, painted	.01	.01	.02	.02	.02	.03	1
Concrete, poured, exposed, unpainted	.01	.01	.02	.02	.02	.03	3
same, painted	.01	.01	.01	.02	.02	.02	3
Concrete block, exposed, unpainted	.36	.44	.31	.29	.39	.25	1
same, painted	.10	.05	.06	.07	.09	.08	1
Floors							
concrete or terrazzo	.01	.01	.01	.02	.02	.02	1
linoleum, asphalt, rubber or cork tile on concrete	.02	.03	.03	.03	.03	.02	1
parquet flooring with subfloors on sleepers	.05	.03	.06	.09	.10	.20	6
parquet flooring in asphalt on concrete	.04	.04	.07	.06	.06	.07	1
varnished wood joist floor	.15	.11	.10	.07	.06	.07	4
wood platform with large space beneath	.40	.30	.20	.17	.15	.10	3
Glass, large panes of heavy plate glass	.18	.06	.04	.03	.02	.02	1
ordinary window	.35	.25	.18	.12	.07	.04	1
Gypsum board, 1/2", nailed to 2"x4"-s, 16"o.c.	.29	.10	.05	.04	.07	.09	1
Marble or glazed tile	.01	.01	.01	.01	.02	.02	1
Plasters							
gypsum or lime, smooth finish on tile or brick	.01	.01	.02	.03	.04	.05	1
same, on metal lath	.08	.06	.05	.04	.04	.04	7
same, on lath, over air space or on joists or studs	.30	.15	.10	.05	.04	.05	5

Table E.2. Sound absorption coefficients of acoustically efficient absorbing materials

Description	frequency cps						Source
	125	250	500	1000	2000	4000	
Acoustical plaster ("Zonolite") 1/2", trowel application	.31	.32	.52	.81	.88	.84	11
same, 1" thick	.25	.45	.78	.92	.89	.87	11
Acoustile, surface glazed and perforated structural clay tile, perforated surface backed with 1" glass fiber blanket of 1 lb/ft^3 density	.26	.57	.63	.96	.44	.56	9
Fiberboards							
1/2" normal soft, mounted against solid backing, unpainted	.05	.10	.15	.25	.30	.30	5
same, painted	.05	.10	.10	.10	.10	.15	5
1/2", normal soft, mounted over 1" air space, unpainted	.30		.30		.30		5
same, painted	.30		.15		.10		5
Fiberglas insulation blankets							
AF100, 1", mounting # 4	.07	.23	.42	.77	.73	.70	11
same, 2", mounting # 4	.19	.51	.79	.92	.82	.78	11
AF530, 1", mounting # 4	.09	.25	.60	.81	.75	.74	11
same, 2", mounting # 4	.20	.56	.89	.93	.84	.80	11
same, 4", mounting # 4	.39	.91	.99	.98	.93	.88	11
Flexboard, 3/16" unperforated cement-asbestos board, mounted over 2" air space	.18	.11	.09	.07	.03	.03	10
Geocoustic, 13 1/2"x 13 1/2", 2" thick cellular glass tile, installed 32" o.c., per unit	.13	.74	2.35	2.53	2.03	1.73	8
Hardboard panel, 1/8", 1 lb/ft^2 with bituminous roofing felt stuck to back, mounted over 2" air space	.90	.45	.25	.15	.10	.10	5

Table E.2. Sound absorption coefficients of acoustically efficient absorbing materials - cont'd.

Description	frequency cps						Source
	125	250	500	1000	2000	4000	
Masonite							
$\frac{1}{4}$", mounted over 1" air space	.12	.28	.19	.18	.19	.15	7
Mineral or glass wool blanket, 1", 5-12 lb/ft^3 density, mounted against solid backing, covered with open-weave fabric	.15	.35	.70	.85	.90	.90	5
same, covered with 5% perforated hardboard	.10	.35	.85	.85	.35	.15	5
same, covered with 10% perforated or 20% slotted hardboard	.15	.30	.75	.85	.75	.40	5
Mineral or glass wool blanket, 2", 5-12 lb/ft^3 density, mounted over 1" air space, covered with open-weave fabric	.35	.70	.90	.90	.95	.90	5
same, covered with 10% perforated or 20% slotted hardboard	.40	.80	.90	.85	.75	.40	5
Plywood panels							
$\frac{1}{4}$", glued to $2\frac{1}{2}$" thick plaster wall on metal lath	.05		.05		.02		3
$\frac{1}{4}$", mounted over 3" air space, with 1" glass-fiber batts right behind the panel	.60	.30	.10	.09	.09	.09	7

Table E.2. Sound absorption coefficients of acoustically efficient absorbing materials - contd.

Description	frequency cps 125	250	500	1000	2000	4000	Source
Rockwool blanket, 2" thick batt ("Semi-Thik"), mounted against solid backing	.34	.52	.94	.83	.81	.69	10
mounted over 1" air space	.36	.62	.99	.92	.92	.86	10
mounted over 2" air space	.31	.70	.99	.98	.92	.84	10
Rockwool blanket, 2" thick batt ("Semi-Thik"), covered with 3/16" thick perforated cement-asbestos board (Transite), 11% open area, mounted against solid backing	.23	.53	.99	.91	.62	.84	10
mounted over 1" air space	.39	.77	.99	.83	.58	.50	10
mounted over 2" air space	.39	.67	.99	.92	.58	.48	10
Rockwool blanket, 4" thick batt ("Full-Thik"), mounted against solid backing	.28	.59	.88	.88	.88	.72	10
mounted over 1" air space	.41	.81	.99	.99	.92	.83	10
mounted over 2" air space	.52	.89	.99	.98	.94	.86	10
Rockwool blanket, 4" thick batt ("Full-Thik"), covered with 3/16" perforated cement-asbestos board (Transite), 11% open area, mounted against solid backing	.50	.88	.99	.75	.56	.45	10
mounted over 1" air space	.44	.88	.99	.88	.70	.30	10
mounted over 2" air space	.62	.89	.99	.92	.70	.58	10
Roofing felt, bituminous, two layers, 0.8 lb/ft^2, mounted over 10" air space	.50	.30	.20	.10	.10	.10	5

Table E.2. Sound absorption coefficients of acoustically efficient absorbing materials - contd.

Description	frequency cps						Source
	125	250	500	1000	2000	4000	
Spincoustic blanket							
1", mounted against solid backing	.13	.38	.79	.92	.83	.76	1
2", mounted against solid backing	.45	.77	.99	.99	.91	.78	1
Spincoustic blanket, 2" thick, covered with 3/16" thick perforated cement-asbestos board (Transite), 11% open area	.25	.80	.99	.93	.72	.58	10
Sprayed "Limpet" asbestos							
¾", 1 coat, unpainted, on solid backing	.08	.19	.70	.89	.95	.85	11
same, 1" thick	.30	.42	.74	.96	.95	.96	11
¾", 1 coat, unpainted, on metal lath	.41	.88	.90	.88	.91	.81	11
Transite, 3/16" perforated cement-asbestos board, 11% open area							
mounted against solid backing	.01	.02	.02	.05	.03	.08	10
mounted over 1" air space	.02	.05	.06	.16	.19	.12	10
mounted over 2" air space	.02	.03	.12	.27	.06	.09	10
mounted over 4" air space	.02	.05	.17	.17	.11	.17	10
paper-backed board, mounted over 4" air space	.34	.57	.77	.79	.43	.45	10
Wood paneling, 3/8" to ½" thick, mounted over 2" to 4" air space	.30	.25	.20	.17	.15	.10	3

Table E.3. Sound absorption coefficients of room contents

Description	frequency cps						Source
	125	250	500	1000	2000	4000	
Air (x), per ft^3	nil	nil	nil	.001	.002	.006	5
Audience and seats							
audience, seated in upholstered seats, per ft^2 of floor area	.60	.74	.88	.96	.93	.85	1
unoccupied cloth-covered upholstered seats, per ft^2 of floor area	.49	.66	.80	.88	.82	.70	1
unoccupied leather-covered upholstered seats, per ft^2 of floor area	.44	.54	.60	.62	.58	.50	1
wooden pews, occupied, per ft^2 of floor area	.57	.61	.75	.86	.91	.86	1
chairs, metal or wood seats, each, unoccupied	.15	.19	.22	.39	.38	.30	1
Carpets							
heavy, on concrete	.02	.06	.14	.37	.60	.65	1
same, on 40 oz hairfelt or foam rubber	.08	.24	.57	.69	.71	.73	1
same, with impermeable latex backing, on 40 oz hairfelt or foam rubber	.08	.27	.39	.34	.48	.63	1
Curtains							
light velour, 10 oz per yd^2, hung straight, in contact with wall	.03	.04	.11	.17	.24	.35	1
medium velour, 14 oz per yd^2, draped to half area	.07	.31	.49	.75	.70	.60	1

Table E.3. Sound absorption coefficients of room contents - cont'd.

Description	frequency cps						Source
	125	250	500	1000	2000	4000	
heavy velour, 18 oz per yd^2, draped to half area	.14	.35	.55	.72	.70	.65	1
heavy curtain, 3½" from rigid backing	.06	.10	.38	.63	.70	.73	4
Fiberglas curtain, 6.1 oz per yd^2, draped to half area, 5" from rigid backing	.08	.13	.21	.29	.23	.29	8
same, 8.4 oz per yd^2	.09	.32	.68	.83	.76	.76	8
Musician, with seat and instrument, per person	4.0	8.5	11.5	14.0	13.0	12.0	5
Openings							
deep balcony, ratio of balcony depth to height: 2½	.30		.50		.60		2
same, with ratio: 3	.40		.65		.75		2
stage opening, unspecified	.30		.40		.50		2
ventilating grilles, 50% open area	.30		.50		.50		2
Water surface, as in swimming pool	.01	.01	.01	.015	.02	.025	1

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relative to Section E, "Sound Absorbing Materials and Constructions"

(See list of abbreviations on page 1)

Books, booklets, chapters of books

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E-14 The effect of humidity upon the absorption of sound in a room, and a determination of the coefficients of absorption of sound in air by V.O. Knudsen. J. Acoust. Soc. Am., Vol. 3, July 1931, p. 126-138.

E-15 Dependence of sound absorption upon area and distribution of absorbent materials by V.L. Chrisler. J. Res. Nat. Bur. Stand., Vol. 13, 1934, p. 169.

E-16 Die Schallabsorption schwingungsfähiger Platten by H. Lauffer. Hochfreq. Tech. Elektr. Akust., Vol. 49, 1937, p. 9-20.

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E-20 Acoustic impedance of commercial materials and the performance of rectangular rooms with one treated surface by L.L. Beranek. J. Acoust. Soc. Am., Vol. 12, July 1940, p. 14-23.

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Section F. Acoustical Requirements in Auditorium Design

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  F.6.5 Coupled spaces
  F.6.6 Distortion
  F.6.7 Room resonance
  F.6.8 Sound shadows
  F.6.9 Whispering galleries

F.7 Noise and vibration control of Auditoria

References

F.1 General considerations in the architectural design of rooms

The architectural design of the various types of Auditoria - an extremely complex problem - has to comply with aesthetical, functional, constructional, economical and various hygienic (environmental) requirements. Besides the architecturally pleasant and structurally sound arrangement of an Auditorium, particular care has to be taken in order to provide comfortable accommodation, good sight and hearing, proper temperature, ventilation, light, etc., at reasonable and proportionate cost. The listeners should be able to reach their seats easily and rapidly, and the room should be capable of being evacuated quickly and safely in case of an emergency or at the end of a performance (F-3, F-4, F-5).

To sum up, the audience in a contemporary Auditorium expects comfort, safety, pleasant aesthetics, proper light, good sight and good sound. Subsequent paragraphs review one of these requirements, namely good hearing.

F.2 Acoustical requirements in room design

The following are the requirements for good hearing conditions in an Auditorium (F-1, F-2, F-4, F-12, F-14, F-27, F-30, F-35, F-36, F-51, F-54, F-57, F-60, F-62):

(1) there should be adequate loudness in every part of the Auditorium, particularly at those seats which are furthest away from the sound source;

(2) there should be a uniform distribution of sound energy in every part of the room, i.e., the sound should be equally loud at all seats whether they be near or remote;

(3) the Auditorium should have optimum reverberation characteristics that will allow (a) the most favorable appreciation of the sound program, i.e., high intel-

ligibility of the spoken word or full enjoyment of music, as the case may be, and (b) the most efficient presentation of the sound program by the performers;

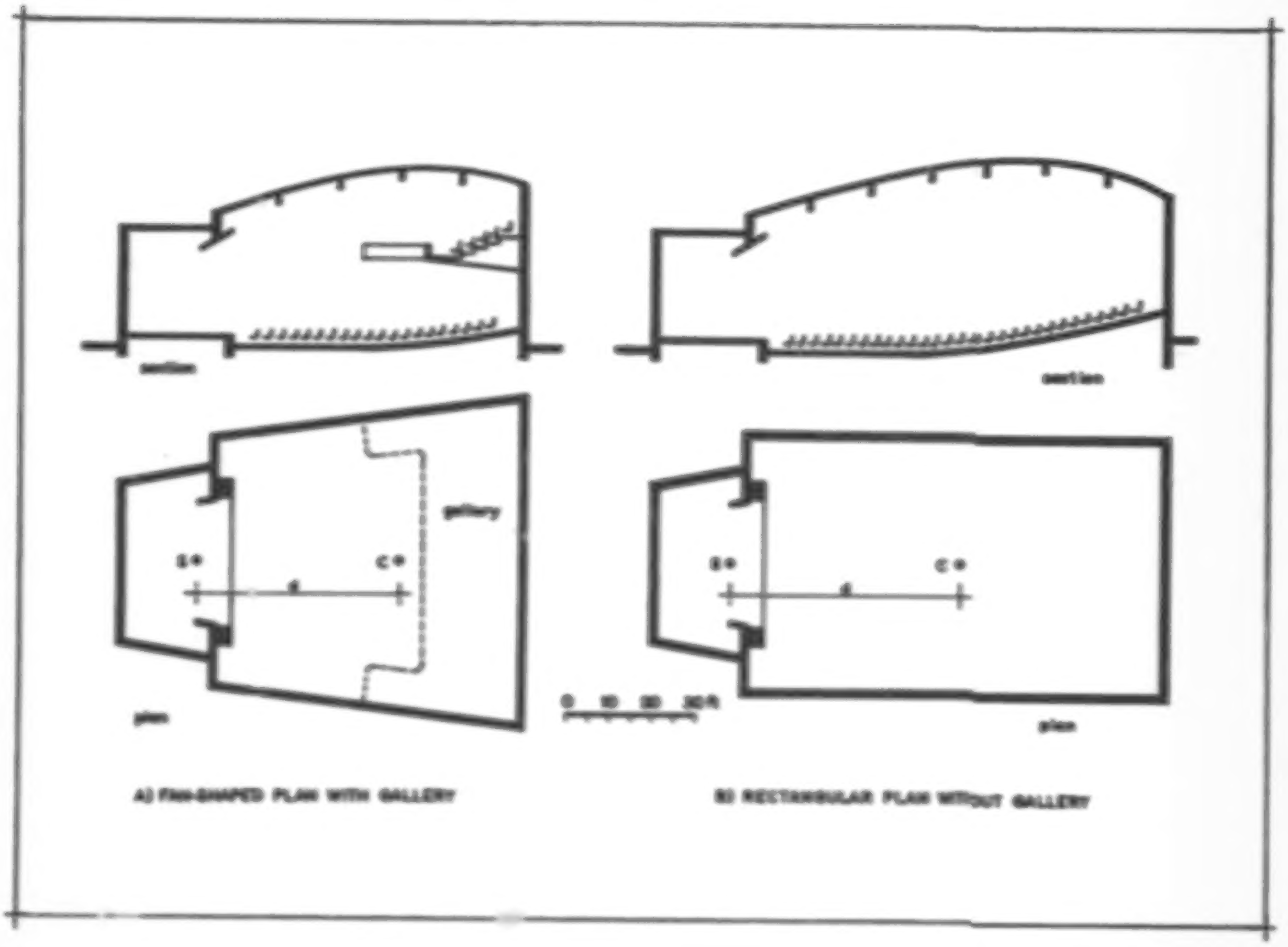
(4) the Auditorium should be free from acoustical defects; such as, echoes, long-delayed reflections, flutter echoes, sound concentrations, distortion, room resonance, sound shadows or other undesirable phenomena;

(5) noises and vibrations, which would interfere with the performance or listening in the Auditorium, should be excluded or reasonably reduced from every part of the room.

F.3 Importance of room shape and volume for the proper supply of sound energy

The shape and size of an Auditorium are factors of outstanding importance in the achievement of adequate loudness in every part of the audience area. This problem, particularly in medium and large Auditoria, is brought about by the energy losses of the traveling sound waves and by the sound absorption due to acoustical finishes and room contents. These sound energy losses must be reduced to a minimum and also replaced in the following ways (F-1, F-2, F-6, F-16, F-30, F-36, F-54, F-61, GB-43, GB-52, GB-53):

(A) The shape of the Auditorium plan should be established such that the audience can be located as close as possible to the sound source, thereby reducing the distance the sound has to travel. This will suggest the preference for a tapering (fan shaped) plan as against a rectangular plan. In larger Auditoria the introduction of a gallery (or galleries) brings more seats closer to the sound source, as illustrated in Figure F.1.


section
section
gallery
S
C
d
S
C
d
plan
plan
0 10 20 30 ft

A) FAN-SHAPED PLAN WITH GALLERY

B) RECTANGULAR PLAN WITHOUT GALLERY

Figure F.1. In an Auditorium with non-parallel side walls and gallery (A), the audience can be seated closer to the sound source as against a rectangular plan of the same capacity but without gallery. C = center of gravity of listening area, S = sound source, d = average distance between sound source and listener.

(B) The floor area and the volume of the room should be kept at a reasonable minimum, thereby shortening the distance the direct and reflected sound has to travel (F-55).

(C) The audience should be located on a properly raked or ramped floor because sound is more readily absorbed when it travels over the audience at grazing incidence (F-61).

(D) The sound source should be raised as much as possible in order to secure a free flow of the direct sound waves (those traveling directly from the sound source, without reflection) to every auditor.

(E) The sound source should be closely and abundantly surrounded with efficient (flat or slightly convex) sound reflective surfaces in order to supply additional reflected sound to every portion of the audience area but particularly to the remote seats. The angles of the reflective surfaces must be established by the law of sound reflection outlined in paragraph D.1. The provision of large sound reflectors around the sound source is a prerequisite of good hearing conditions in Auditoria (F-8, F-11, F-26, F-27, F-38, F-59).

The audience should be seated not only close to the sound source but should also occupy those parts of the seating area which are most valuable from the point of view of both sight and hearing. To avoid acoustically inadequate seats at the extreme ends of front rows (in an Auditorium with excessive width compared to its length), the floor plan should be well proportioned; practically speaking, the average width to maximum length proportion should fall between 1:1.2 and 1:2.2 (F-1). No aisle should be located along the longitudinal axis of an Auditorium, since seeing and hearing conditions are most favorable along this line (F-1, GB-52).

In regard to the ratio of height to width to length of an Auditorium, the older acoustical literature contains a number of pertinent suggestions; rigorous adherence to these proportions was considered to be an indispensable factor in the achievement of perfect room acoustical conditions. Popular formulae give the ratio of height : width : length = 2 : 3 : 5 or 1 : $\sqrt[3]{2}$; $\sqrt[3]{4}$ (GB-52). The acoustical efficiency of these proportions is unquestionable, however, it must be mentioned that the strict consideration of any recommended room proportions should be limited to the design of acoustically sensitive rooms, such as Radio or Recording Studios, etc. (discussed in Section J).

In the design of acoustically efficient reflective surfaces around the sound source it must be remembered that (a) the reflectors have to be located closely to the sound source in order to produce powerful reflections following quickly upon the direct sound, (b) the reflections need to be progressively more and numerous towards the remote seats (GB-53), and (c) the dimensions of the reflecting surfaces must be comparable to the wavelengths of the sound waves to be reflected (as pointed out in subsection D.1). The ceiling usually constitutes a suitable surface for the accommodation of sound reflectors, as illustrated diagrammatically in Figure F.2. In reality, the successful integration of an acoustically efficient system of ceiling reflectors into the overall architectural, structural, mechanical, and electrical layout of the ceiling is one of the most difficult problems in the design of a contemporary Auditorium. It will definitely require full attention from the architect, and his close cooperation with structural, mechanical, electrical and acoustical consultants will be particularly important. For additional examples of acoustically efficient ceiling reflectors see Figures G.8, H.1, H.2, I.5 and I.6.

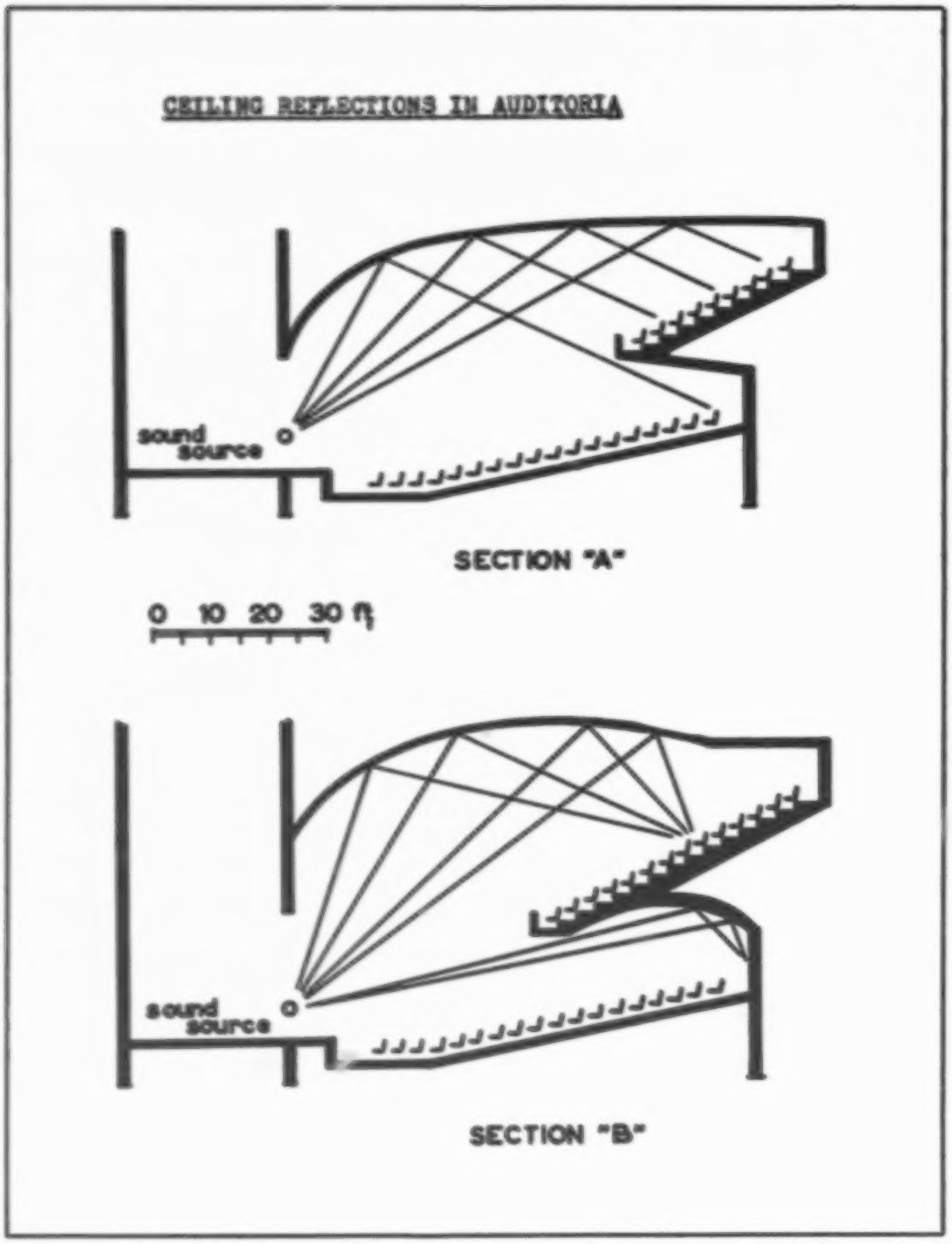

CEILING REFLECTIONS IN AUDITORIA
sound source
SECTION "A"
0 10 20 30 ft
sound source
SECTION "B"

Figure F.2. A properly shaped ceiling reflector (Section "A") will provide uniform sound energy distribution over the remote rows. A poorly shaped ceiling (Section "B") will create acoustically poor spots.

Parallel boundary surfaces, particularly close to the sound source, should be avoided in the design of the room shape.

In addition to those reflective surfaces which serve to reinforce the direct sound by reflections toward the audience, additional reflective surfaces have to be provided which will direct the sound back to the performers. This is particularly necessary in Auditoria designed for musical or vocal purposes (GB-43).

If besides the primary sound source,generally located at the front part of the Auditorium, additional sound sources exist in other parts of the room (e.g., Church organ or choir gallery opposite the altar end of the nave), these sound sources also have to be surrounded by sound reflective surfaces. It is essential that in every Auditorium a condition be created under which the greatest possible amount of sound energy is directed from all "sending" positions to all "receiving" areas.

Correctly located sound reflectors, in addition to providing for the required reinforcement of the sound energy supply, also create an environmental condition known as "space effect", which is brought about when sound is received by an auditor from numerous directions; this condition is typical of an enclosed space and entirely missing in an Open-Air Theater.

The proper design and location of sound reflective surfaces will compensate adequately for the sound energy losses in small and medium size rooms. In large Auditoria, however, the design of a high-quality sound amplification system is indispensable (F-1); sound systems will be discussed in Section L.

Galleries should not protrude too far into the air space of an Auditorium, since the audience seated below deep galleries can hardly, if at all, be supplied with sufficient direct and reflected sound energy (see paragraph F.6.8).

F.4 Provision for diffusion of sound

If the sound energy is uniformly distributed in an Auditorium (requirement No. 2 of subsection F.2) and the sound waves are traveling in every direction, the phenomenon of acoustical diffusion will be experienced (F-33, F-38). Subsection D.4 has described the ways in which acoustical diffusion can be achieved. Two important aspects have to be considered in the effort to provide diffusion in a room: the surface irregularities must be abundantly applied and they must be of reasonably large size (F-1, F-2, F-10, F-28, F-33, F-54).

For reasons of economy and aesthetics, particularly in small rooms, the application of surface irregularities is often difficult. In such cases, the random distribution of absorbing material or the alternate application of sound reflective and sound absorptive treatment are other means of promoting diffusion.

The application of acoustical diffusers is particularly important for Concert Halls, Opera Houses, Radio and Recording Studios and Music Rooms. For examples of efficiently applied acoustical diffusers see Figures G.2, H.1, H.2, H.10, H.12 and I.7.

The beneficial effect of acoustical diffusers upon the acoustical conditions of Auditoria is quite remarkable. It has been found that in certain rooms with rather excessive reverberation times, in which a reasonable number of properly sized surface irregularities have been installed, hearing conditions are better than is normally expected (GB-52). This is probably due to the fact that the diffusers have created a uniformity in the rate of growth and decay of the transient sounds (see subsection D.5).

F.5 Control of reverberation time

For every Auditorium there exist optimum reverberation characteristics that will enable all frequency components of speech and music to grow and decay at such rates during their transient states, and to be maintained at such levels during their steady states, as will result in perfect intelligibility of speech and ideal conditions for the production, transmission and appreciation of music (F-1). Optimum reverberation characteristics of a room, depending on its volume and function, implies (a) favorable R.T. vs. frequency characteristics, (b) propitious ratio of reverberant to direct sound reaching the audience (F-27), and (c) optimum nature of the growth and decay of sound (F-1, F-2, F-4, F-34, F-36, GB-43, GB-52).

At present the control of R.T. is a most important step in the acoustical design of Auditoria. The optimum R.T. of an Auditorium is represented by a diagram which gives ideal values of R.T. as functions of representative frequencies throughout the audio-frequency range.

Figure F.3 gives a reasonable summary of optimum reverberation times of Auditoria, plotted against their volume, as recommended by the following authorities: V.O. Knudsen and C.M. Harris (F-1), F. Ingerslev (F-2), Acoustical Materials Association, New York (F-4), F. Bruckmayer (F-60), B.Y. Kinzey and H.M. Sharp (F-62), W. Kuhl (J-71), L.L. Beranek (GB-34), P.H. Parkin and H.R. Humphreys (GB-43), and W. Furrer (GB-52). The reverberation times shown on Figure F.3 apply to the mid-frequency region of 500 to 1000 cps; these values usually serve as reliable factors of the hearing conditions in Auditoria. Experience has proved that excessive variation of R.T. at frequencies other than the mid-frequency value will create unsatisfactory hearing conditions. Various curves of R.T. vs. frequency have been suggested (F-1, GB-34); these generally recommend a flat curve above 500 cps. For music, a curve rising to about 1.5 times the 500 cps value at 125 cps

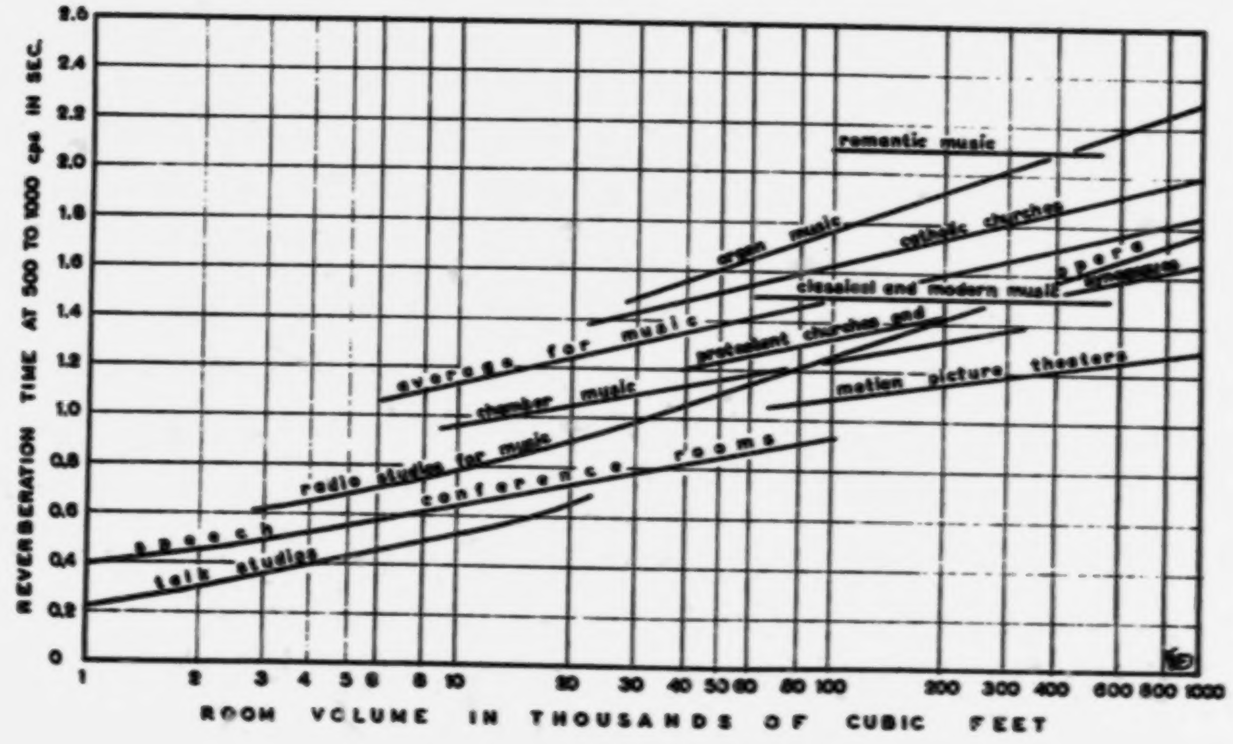


Figure F.3. Optimum reverberation times for Auditoria of various sizes and functions, at the frequency of 500 cps, compiled from published literature.

is proposed, while for speech, the curve should remain flat down to 100 cps. For Multi-Purpose Auditoria, the R.T. vs. frequency curve below 500 cps may lie anywhere between these limits (F-4). A deviation of about 5 to 10 % from a selected optimum R.T. value is generally considered acceptable, particularly in Auditoria with a high degree of diffusion. Figure F.3 clearly indicates that rooms used for speech require a shorter R.T. than rooms of the same volume used for musical or vocal purposes; these aspects will be described in Section G, "Acoustical Design of Rooms for Speech", and in Section H, "Acoustical Design of Rooms for Music".

During the acoustical design of an Auditorium, once the optimum R.T. at the mid-frequency range has been selected, and the R.T. vs. frequency relationship below 500 cps settled, then the reverberation control consists of establishing the total amount of room absorption to be supplied by the room finishes, room contents, etc., that will produce the selected value of R.T. For this calculation, the formula discussed in paragraph D.5, is used (F-1, F-44, F-48, GB-43, GB-52):

$$\text{R.T.} = \frac{0.049\ V}{S\left[-2.30\ \log_{10}\ (1-\bar{\alpha})\right] + xV}$$

This formula distinctly shows that the larger the room volume, the longer will be the R.T., and that the more absorption introduced into the room, the shorter will be the R.T. Tables F.1 and F.2 illustrate the effect of room volume and audience absorption on R.T. in various Auditoria reputed for their acoustics.

The distribution and selection of the most suitable acoustical treatments, under given circumstances, have been discussed in subsections E.7 and E.8. As a general rule, absorbing materials should be placed along those boundary surfaces of the Auditorium which are liable to produce acous-

Table F.1

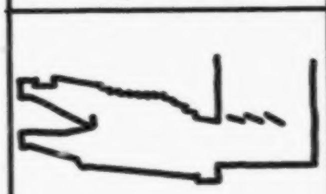
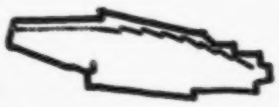
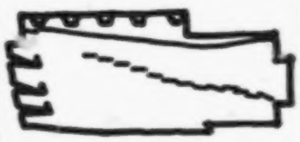
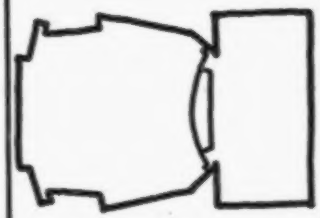
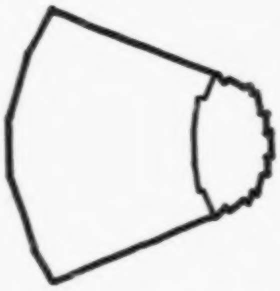
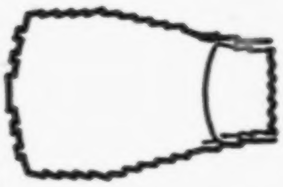
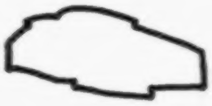
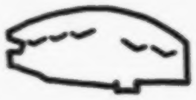
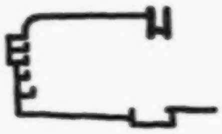
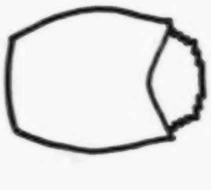
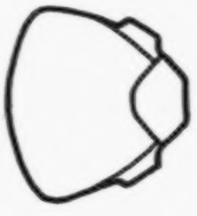
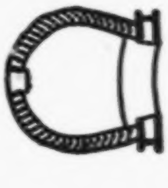
EFFECT OF ROOM VOLUME ON REVERBERATION TIME			
	Queen Elizabeth Theater, Vancouver	F.R.Mann Concert Hall, Tel-Aviv, Israel	Philharmonic Hall, New York
Longitudinal Sections			
Floor plans			
Volume (ft^3)	525,500	750,000	865,000
Number of seats	2800	2715	2644
Volume per seat (ft^3)	188	276	327
Mid-frequency reverberation time (sec)	1,35	1,55	1,9
Year of dedication	1959	1957	1962

Table F.2

EFFECT OF ROOM ABSORPTION ON REVERBERATION TIME			
	Concert Hall Turku, Finland	Kresge Auditorium, Cambridge, U.S.A.	Teatro Alla Scala, Milan, Italy
Longitudinal Sections			
Floor plans			
Volume (ft^3)	340,000	354,000	397,000
Number of seats	1002	1238	2289
Audience area (ft^2)	5000	9280	14,000
Mid-frequency reverberation time (sec)	1,6	1,47	1,2
Year of dedication	1953	1955	1778

tical defects; such as, echoes, too long-delayed reflections, sound concentrations, etc. (to be discussed in subsection F.6).

In Auditoria with widely fluctuating audience attendance, hearing conditions should also be satisfactory in the partial or total absence of the audience. The most effective way, though certainly not inexpensive, to achieve this is to replace the possible loss of audience absorption by upholstered seats, with the bottom side of the seats also rendered absorptive (F-54).

F.6 Elimination of acoustical defects

Besides the provision for positive acoustical attributes in an Auditorium, such as adequate loudness (subsection F.3), uniform distribution of sound energy (subsection F.4), and the control of reverberation (subsection F.5), it is essential that various acoustical defects should be eliminated from Auditoria. The following are the most common acoustical defects that can impair, and sometimes destroy, otherwise acceptable acoustical conditions within a room:

F.6.1 Echo

This will be noticeable when the sound is being reflected from any boundary surface of the Auditorium with sufficient magnitude and delay to be perceived as a sound distinct from that which travels directly from the sound source (GB-73). Echo occurs if a time interval of 1/10 to 1/25 second elapses between the perception of the direct and reflected sounds originating from the same source. These time intervals correspond to path differences of 45 to 113 ft between direct and reflected sound. The exact time lag between direct and reflected sound that is necessary to produce echo, in other words, the distance between sound source and echo-producing reflective boundary surface, will depend on the type of sound program, the position of sound source and listener, the size and shape of the reflecting surface, reverberation conditions in the room, and sensitivity of the ear.

A sound reflective rear wall, opposite the sound source, is a potential echo-producing surface in an Auditorium (see Figure F.4), unless this rear wall is underneath a deep balcony (F-1, F-2, F-22, GB-43, GB-52, GB-53).

F.6.2 Long-delayed reflections

These are basically echoes with a shorter delay; they produce a blurring or masking of the direct sound (GB-43).

F.6.3 Flutter echo

Consisting of a rapid succession of noticeable echoes, a flutter echo can be observed if a short burst of sound, such as a clap or shot, is produced between parallel, sound reflective surfaces, while the other pairs of opposite surfaces in the room are non-parallel, or relatively absorbent, or diffusive (F-1, F-2, GB-43). Elimination of parallelism between opposite reflecting surfaces is one way to avoid flutter echoes. No flutter echo will be noticeable if the sound source is not located between the critical parallel surfaces.

Echoes, long-delayed reflections and flutter echoes generally can be prevented by the application of sound absorbing materials along the defect-producing reflective surfaces. If the installation of acoustical finishes along these critical areas is not feasible, they should be rendered diffusive, or tilted, to produce beneficial reflections as shown diagrammatically in Figure F.5 (F-1, F-2).

F.6.4 Sound concentrations

Often referred to as "hot" spots, sound concentrations are

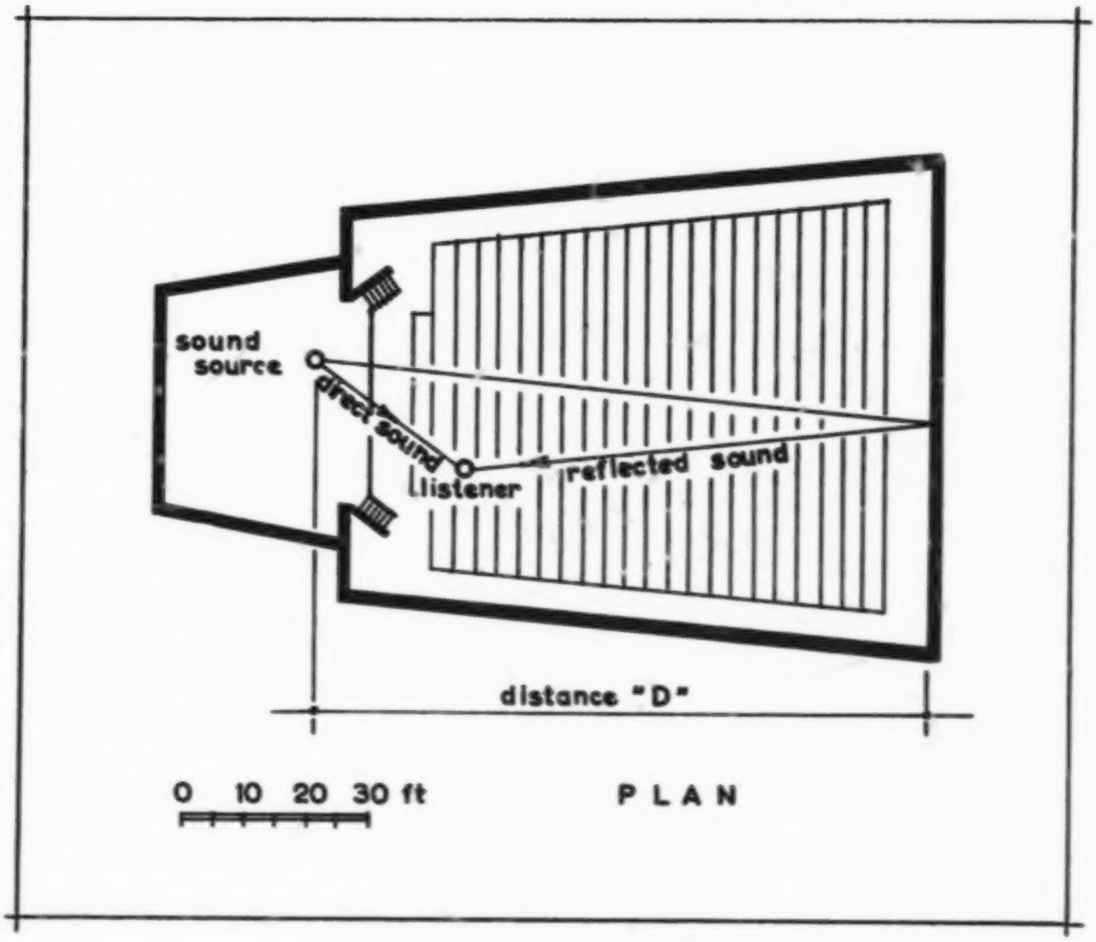

sound source
direct sound
listener
reflected sound
distance "D"
0 10 20 30 ft
PLAN

Figure F.4. The rise of echo in an Auditorium. The distance "D" between sound source and echo - producing rear wall will depend on the type of the sound program, position of sound source and listener, size and shape of reflecting surface, reverberation conditions in the room, and sensitivity of the ear.

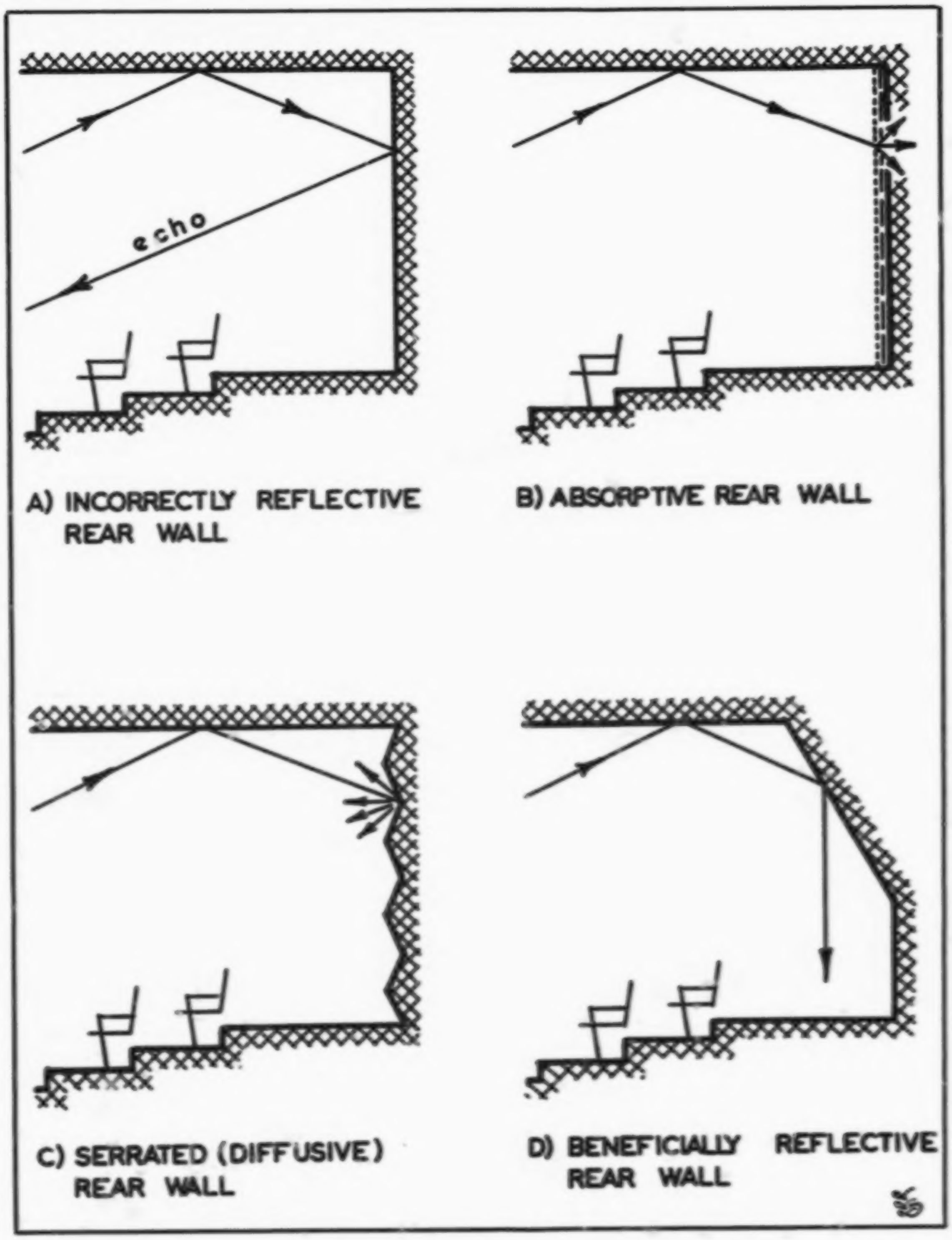

echo
A) INCORRECTLY REFLECTIVE REAR WALL
B) ABSORPTIVE REAR WALL
C) SERRATED (DIFFUSIVE) REAR WALL
D) BENEFICIALLY REFLECTIVE REAR WALL

Figure F.5. Reflective rear wall (A), liable to produce acoustical defects, should be treated acoustically (B), or rendered diffusive (C), or tilted, to produce beneficial reflections (D).

created by sound reflections from concave surfaces. The loudness of sound at these "hot" spots is unnaturally high, which always happens at the expense of other parts of the room, called "dead" spots, where hearing conditions are poor. The presence of "hot" and "dead" spots create a non-uniform distribution of sound energy in rooms (F-1, F-2, GB-43, GB-53); the elimination of this phenomenon is an important goal of room acoustics. A typical example of undesirable sound concentration can be observed near a speaker whose sound is reflected back to him from adjacent concave surfaces, creating the false subjective illusion that he talks too loudly. He will, therefore, overestimate the loudness of his own voice and will be inclined to speak softer than is necessary to be heard by an audience (F-1).

Large, unbroken, concave enclosures, particularly those having large radii of curvature, should be eliminated from Auditoria, or treated with efficient sound absorbing materials. If the application of large concave surfaces cannot be avoided and their acoustical treatment is not feasible, then these concave surfaces should be shaped such that they focus in space outside the audience area or room (F-2).

A suitably selected and properly installed sound amplification system will reduce, but never entirely remedy, the detrimental acoustical effects of echoes, long-delayed reflections, flutter echoes and sound concentrations.

F.6.5 Coupled spaces

If an Auditorium is connected to an adjacent reverberant space (such as a foyer, stair-hall, corridor, stage tower, baptistry, etc.) by means of open doorways, the two rooms will form coupled spaces (F-21). As long as the air spaces of the coupled rooms are interconnected, an inflow of reverberant sound into the main Auditorium from the adjacent space will be noticeable, although reverberation might have been properly controlled in the main room. This phenomenon will particularly disturb the audience seated close to the open doorways, no matter how much consideration was given to the reverberation control of the main Auditorium (F-1, F-2).

The undesirable effect created by coupled spaces can be overcome either by adequate acoustical separation between the coupled spaces or by providing approximately the same decay rate in both spaces.

F.6.6 Distortion

This phenomenon is an undesired change in the quality of musical sounds due to the uneven or excessive sound absorption at different frequencies of boundary surfaces. This will be avoided if the applied acoustical finishes have balanced absorption characteristics over the entire audio-frequency range.

F.6.7 Room resonance

Sometimes called "coloration", this will occur when sounds within a narrow frequency band tend to sound louder than other frequencies. This phenomenon is created by parallel reflective surfaces if the wavelength of the sound is equal to the distance between the surfaces or to a submultiple of it (GB-34). The avoidance of this acoustical defect is particularly important in the design of Broadcasting and Recording Studios.

F.6.8 Sound shadows

Under-balcony spaces, with a depth exceeding twice the height, should be avoided (Figure H.7), since they will prevent the remote seats underneath from receiving an adequate amount of direct and reflected sounds, creating, thereby, poor audibility in this region of the Auditorium (GB-53).

F.6.9 Whispering galleries

High frequencies of sound have the tendency to "creep" along large concave surfaces, such as hemispherical domes (St. Paul's Cathedral in London, Royal Theater in Copenhagen, etc.). A very soft sound like a whisper created close to such a dome will be surprisingly audible at the opposite side of the structure. A whispering gallery might be a sensational and harmless phenomenon in an Auditorium but never a contributing factor to its acoustics (F-1, F-2).

F.7 Noise and vibration control of Auditoria

The exclusion or reasonable reduction of interfering noises and vibrations from Auditoria, constituting an important requirement in the acoustical design of rooms, will be discussed in detail in PART III NOISE CONTROL (F-35).

References

relative to Section F, "Acoustical Requirements in Auditorium Design"

(See list of abbreviations on page 1)

Chapters of books

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F-23 Pulse methods in the acoustic analysis of rooms by J. Moir. J. SMPTE, Vol. 57, Ag. 1951, p. 147-155.

F-24 Use of artificial reverberation in the Theater (in French) by A. Moles. Ann. Télécomm., Vol. 6, Ag.-Sep. 1951, p. 245-249.

F-25 L'acoustique des salles du point de vue du chanteur et de l'orateur by R. Husson. Ann. Télécomm., Feb. 1952, p. 58-74.

F-26 Bemerkungen zur geometrischen Raumakustik by E. Meyer and W. Kuhl. Acustica, Vol. 2, No. 2, 1952, p. 77-83.

F-27 The effect of direct and reflected sound on the sound distribution in rooms (in German) by J. Grunert. Tech. Hausmitt. NWDR, Vol. 4, July-Ag. 1952, p. 138-141.

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+ F-50 The audience and room acoustics (contained in "Proceedings of the 3rd International Congress on Acoustics, Stuttgart 1959") by A.F.B. Nickson and R.W. Muncey. Elsevier Publishing Company, Amsterdam, 1960, p. 936-938.

+	F-51	Acoustics and architecture in Auditorium design (contained in "Proceedings of the 3rd International Congress on Acoustics, Stuttgart 1959") by W. E. Rossman. Elsevier Publishing Company, Amsterdam, 1960, p. 938-940.
+	F-52	On the acoustics of large halls (contained in "Proceedings of the 3rd International Congress on Acoustics, Stuttgart 1959") by V.M.A. Peutz. Elsevier Publishing Company, Amsterdam, 1960, p. 941-943.
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	F-55	Volume per seat and variation of the reverberation time with the size of the audience by J.R. Carbonell and J.L. Zuccoli. J. Acoust. Soc. Am., Vol. 33, June 1961, p. 757-759.
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Section G. Acoustical Design of Rooms for Speech

- G.1 Nature of speech sounds
- G.2 Effects of rooms on speech
- G.3 Acoustical requirements of Auditoria for speech
- G.4 Auditoria for speech
    - G.4.1 Legitimate Theaters
    - G.4.2 Lecture Halls, Classrooms
    - G.4.3 Assembly Halls, Congress Halls
    - G.4.4 Conference Rooms, Court Rooms, Chambers for Local and National Government
    - G.4.5 Gymnasia, Arenas, Swimming Pools, Bowling Alleys
- References

In the acoustical design of Auditoria for speech the primary requirement is intelligibility, i.e., the speaker should be understood clearly and easily (G-3).

G.1 Nature of speech sounds

Speech sounds contain vowels and consonants, woven into an individual pattern of predominant tones, sometimes called "formants" (GB-73). These formants, consisting mostly of vowels, endow a person's voice with distinctive characteristics, contributing to the basic tone of speech. Consonant sounds, often very high frequency sounds with extremely short and rapid succession, have only a limited acoustical power compared to the vowels.

Vowels emphasize the basic tone and the natural qualities of speech, and since intelligibility depends to a large extent on the proper recognition of consonant sounds, the preservation of both vowels and consonant sounds is therefore an important factor in the achievement of favorable speech acoustics (G-3).

G.2 Effects of rooms on speech

The physical and acoustical features of an Auditorium, such as size and shape of the room, reverberation characteristics, prevailing noise conditions, etc., will have an influence on speech in the room (G-4, G-5, G-6).

The larger an Auditorium is - assuming the absence of a sound amplification system - the more effort must be exerted by a speaker in order to make himself understood in every part of the room but particularly at the remote seats.

Reverberation will reinforce the loudness of speech, however, excessive reverberation will be harmful to intelligibility;

it will blur and mask the spoken syllables by the still audible reverberation of previously uttered syllables (G-7, G-9, G-11). Under such reverberant conditions, a speaker, besides being annoyed, will also be inclined to talk softer, slower and more articulately than he would otherwise (G-1).

G.3 Acoustical requirements of Auditoria for speech

All the requirements and recommendations discussed in Section F, "Acoustical Requirements in Auditorium Design", naturally apply; in particular, the design of rooms for speech must comply with two basic requirements: speech intelligibility must be secured above all, and a R.T. ideal for speech must be provided.

To secure a high degree of intelligibility (G-10) and also to enable the audience to appreciate the subtleties or dramatic effects being sought by a speaker (e.g., actor, preacher, political speaker, etc.), it is essential that:

(A) Ample direct sound waves should reach the listeners; this requires adequately raked seats, a raised speaker's platform and the elimination of any obstructing element (column, deep balcony front) from the room.

(B) The paths of direct sound waves should be as short as possible to reduce sound energy losses in the air. This requires a compact room shape with a low volume per seat value of about 100 to 175 ft^3, preferably nearer to the lower figure (G-3, GB-29). It follows from the R.T. formula that, other conditions being equal, the lower the volume per seat value is in a room, the less acoustical treatment will be required for the provision of the same R.T.

(C) The direct sound waves should be reinforced with ample short-delayed reflections arriving at the listeners with a path difference of possibly not more than about 30 ft compared to the direct sound (G-3).

(D) The seats should be layed out in a pattern such that they do not fall outside an angle of about 140° subtended at the position of the speaker (G-3, G-14, G-17). This is necessary in order to preserve the high frequency speech sounds whose power would drop badly outside this angle, because of their directional characteristics.

(E) The acoustical finishes applied in the Auditorium should possess uniform absorption characteristics between 250 and 7000 cps (G-1) to prevent the undesired excessive absorption of vowels or consonant sounds within this frequency range.

(F) The R.T. of the Auditorium should be as close as possible to the ideal value throughout the entire audio-frequency range, as it is shown in Figure F.3 (G-3). It must be noted, however, that the achievement of a short R.T. alone, as suggested in this Figure, is no guarantee of good hearing conditions in rooms for speech.

The speech intelligibility in an Auditorium can be determined quantitatively by articulation testing which will be discussed in Section K (G-12, GB-73).

G.4 Auditoria for speech

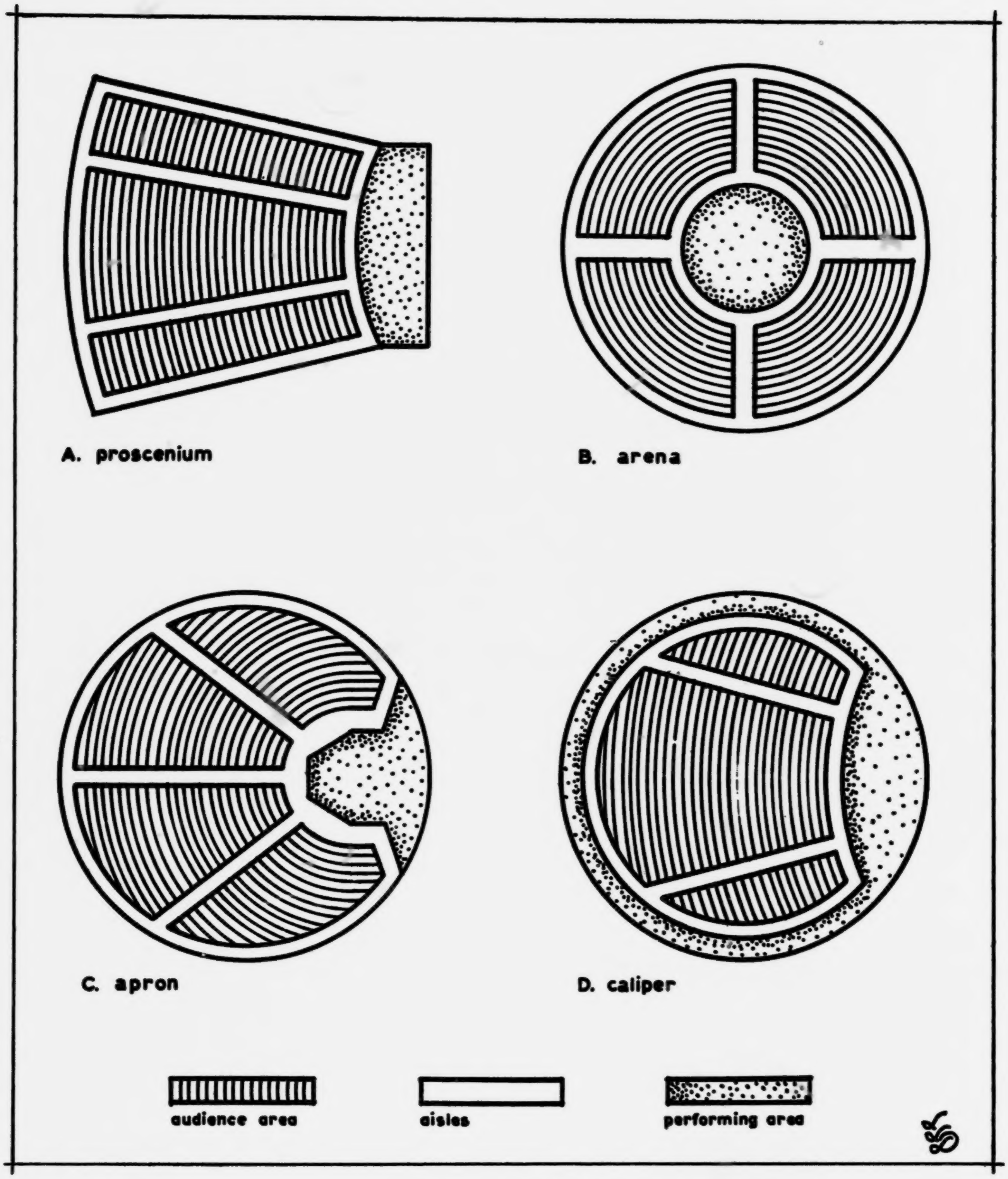
The recommendations given in Section F, "Acoustical Requirements in Auditorium Design", and in subsection G.3, "Acoustical requirements of Auditoria for speech", apply completely to the acoustical design of the various Auditoria discussed in this Section. The architectural and structural design of specific Auditoria, however, will often create special acoustical conditions, thus necessitating the enumeration of a few additional recommendations.

G.4.1 Legitimate Theaters

Consideration will be given here to the Legitimate Theater which is used in the overwhelming majority of performances for regular stage plays (dramatic performances), without dissociating this type of Auditorium from occasional musical presentations (G-15, G-16, G-17, G-68).

Acoustical problems encountered in the architectural design of Legitimate Theaters are ever increasing, due to the fact that fundamental changes are taking place in the domain of Theater design. The Theater people (playwrights, producers, directors, stage managers, composers, actors) expect revolutionary changes from the architects,or at least considerable improvements, in Theater design in order to satisfy their increasing artistic aspirations (G-18, G-24, G-28, G-33, G-39, G-41, G-42, G-46, G-48, G-54, G-56, G-57, G-58, G-62).

The relationship of performing area to audience area, a crucial factor in Theater acoustics, is generally set according to one of four basic stage forms (Figure G.1): (a) the proscenium type (picture stage) with the performing area at one end of the Theater,and with the audience watching through the picture frame of the proscenium opening; it separates the audience from the performers; (b) the arena type (Theater-in-the-round), based on the radial layout of the classical Amphitheaters, without any separation between performers and spectators; (c) the apron type (also called Elizabethan apron) with the performing area protruding into and being surrounded on three sides by the audience, thus providing an intimate relationship between actors and spectators; and (d) the caliper type with the reversed arena concept where the side stages extend out and surround the spectators. Contemporary stage forms all derive from one or a combination of these prototypes (G-33, G-63, G-71).


A. proscenium

B. arena

C. apron

D. caliper

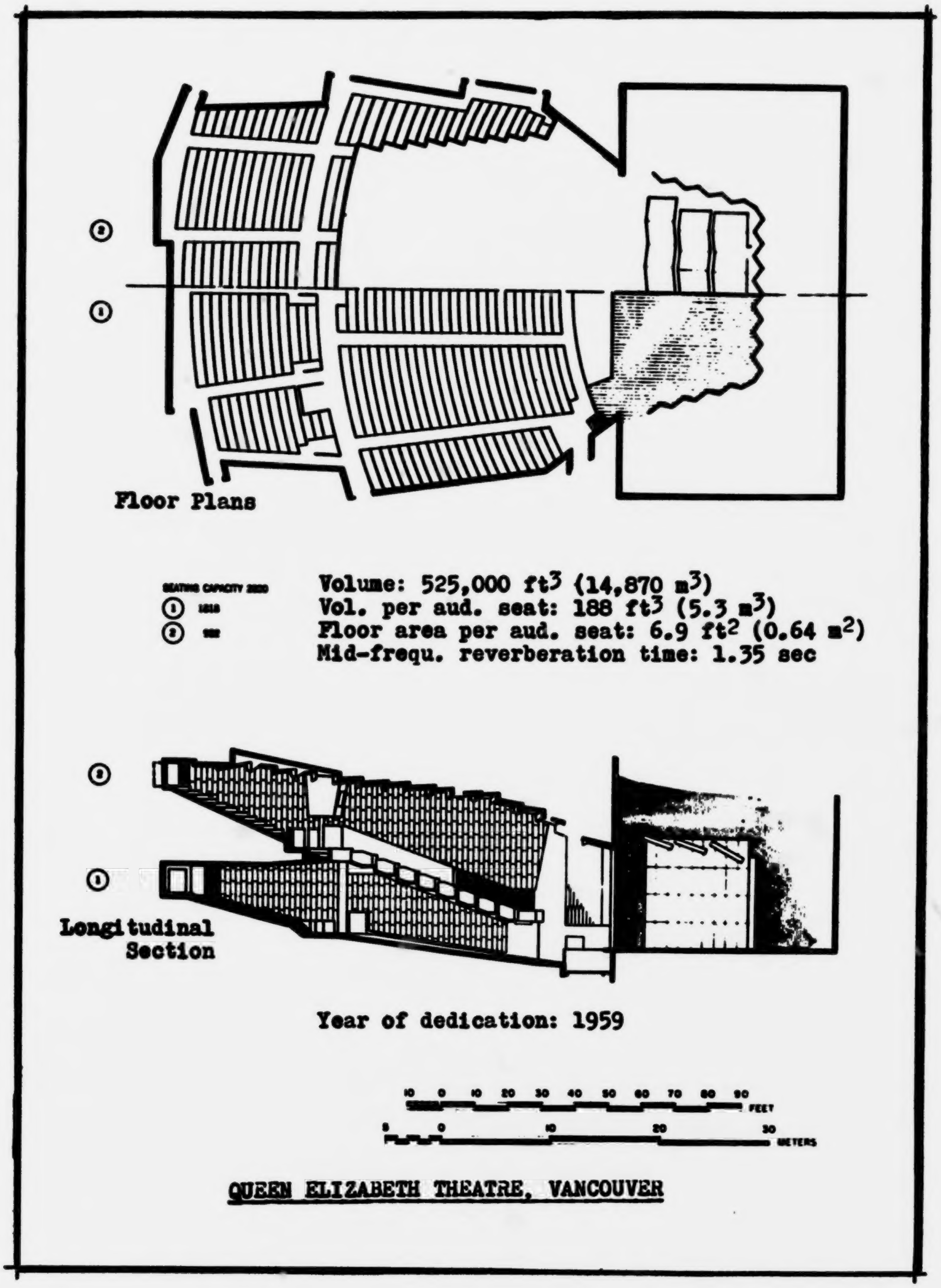
audience area
aisles
performing area

Figure G.1. The basic stage forms used in Theater design.

Figures G.2, G.3 and G.4 show typical examples of the proscenium, arena, and apron type stages (G-13, G-14, G-16, G-19, G-20, G-23, G-25, G-27, G-29, G-30, G-31, G-32, G-35, G-36, G-37, G-44, G-45, G-49, G-55, G-61, G-63, G-64, G-65, G-69, G-71, G-72, G-73).

Regarding the acoustical requirements specifically applicable to Legitimate Theaters, it must be quite obvious that the widely differing floor plans and room shapes will certainly pose serious acoustical problems, in particular:

- providing ample and powerful short-delayed reflections to every part of the audience area;
- securing even distribution of sound throughout the Auditorium;
- raising the sound source and raking the audience area;
- providing short-delayed back reflections onto the performing area;
- obtaining ideal R.T. vs. frequency characteristics for performances other than stage plays;
- eliminating echoes, long-delayed reflections and sound concentrations from the frequently used circular form without creating an overly dead acoustical environment;
- locating the seats such that sufficient sound waves (high frequency components of speech) reach those spectators who happen to sit behind the performer;
- eliminating the coupled space effect between audience area and fly-tower;
- accommodating a sufficiently large and easily demountable orchestra shell on the acting area, with variable capacity;
- installing an unobtrusive, high quality sound amplification system when the audience capacity exceeds about 1500 (G-3).


②
①
Floor Plans
SEATING CAPACITY 2800
① 1818
② 982
②
①
Longitudinal Section
10 0 10 20 30 40 50 60 70 80 90 FEET
5 0 10 20 30 METERS

Volume: 525,000 ft^3 (14,870 m^3)
Vol. per aud. seat: 188 ft^3 (5.3 m^3)
Floor area per aud. seat: 6.9 ft^2 (0.64 m^2)
Mid-frequ. reverberation time: 1.35 sec

Year of dedication: 1959

QUEEN ELIZABETH THEATRE, VANCOUVER

Figure G.2. Queen Elizabeth Theater in Vancouver, B.C., representing the proscenium type stage. Affleck, Desbarats, Dimakopoulos, Lebensold, Michaud and Size, architects; Bolt, Beranek and Newman, acoustical consultants. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

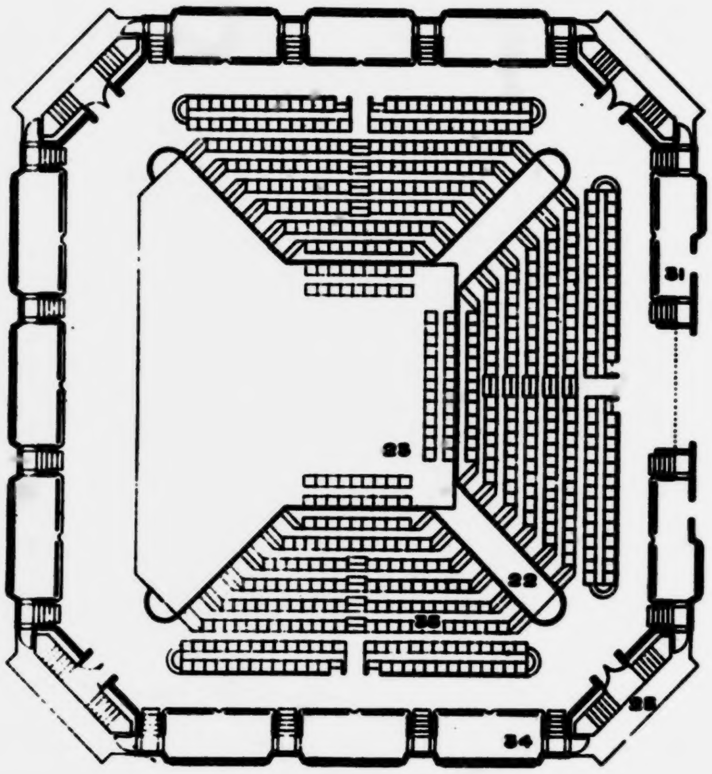


Figure G.3. Arena stage in Washington, D.C. Floor plan. Seating capacity: 752, completed in 1961. 22: stage entrance, 23: stage, 25: smoking balcony, 31 and 34: boxes, 35: tiers. H. Weese and Ass., architects and engineers. (Reprinted from Progr. Arch., Feb. 1962).

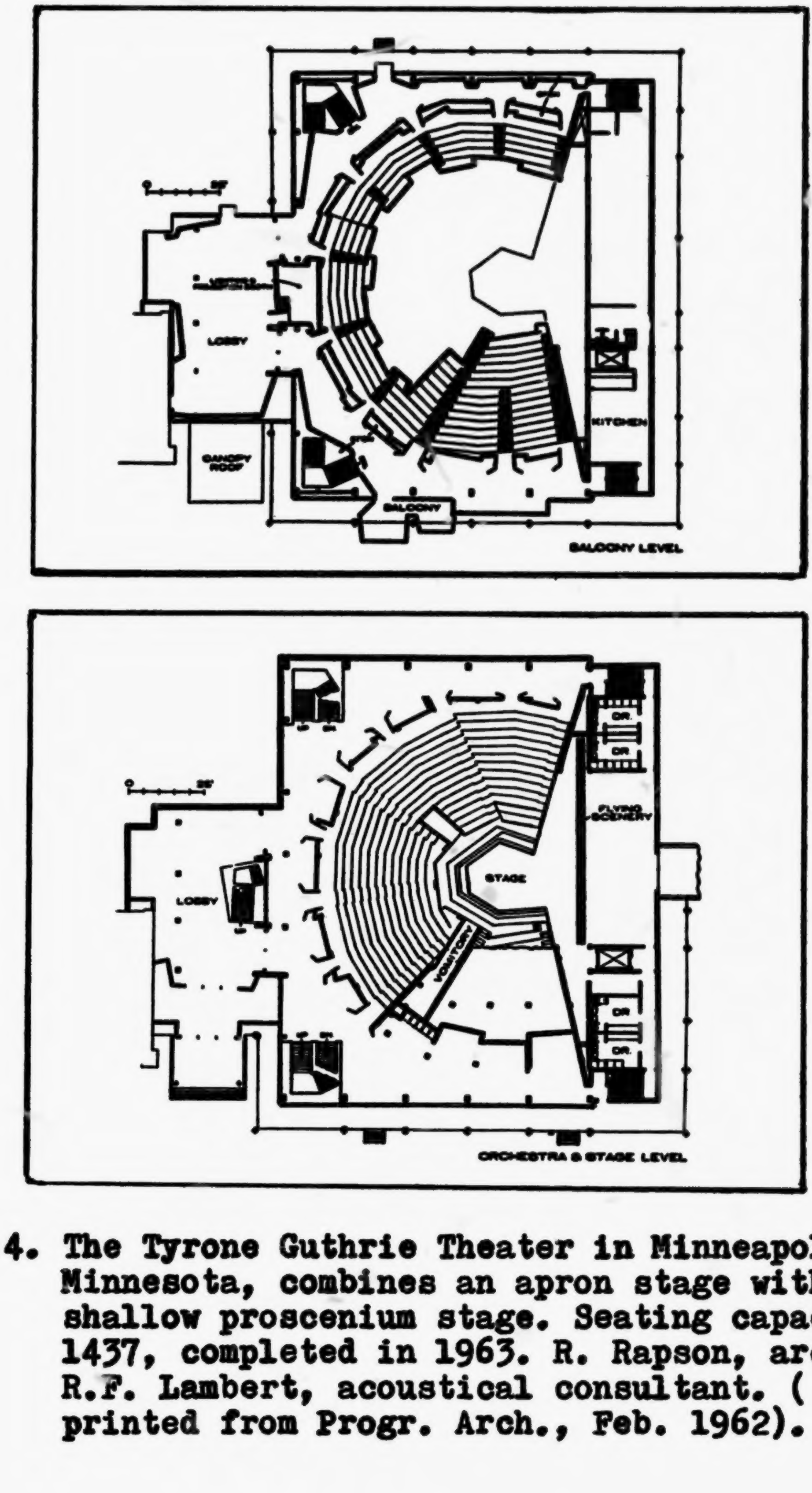

0
25'
LOBBY
CANOPY ROOF
BALCONY
KITCHEN
BALCONY LEVEL
0
25'
LOBBY
STAGE
FLYING SCENERY
DR
DR
DR
DR
VOMITORIA
ORCHESTRA & STAGE LEVEL

Figure G.4. The Tyrone Guthrie Theater in Minneapolis, Minnesota, combines an apron stage with a shallow proscenium stage. Seating capacity: 1437, completed in 1963. R. Rapson, architect; R.F. Lambert, acoustical consultant. (Reprinted from Progr. Arch., Feb. 1962).

G.4.2 Lecture Halls, Classrooms

Lecture Halls of the various educational institutions, often termed "Amphitheaters", and normally seating more than about 100 persons, should be designed in accordance with the relevant acoustical principles discussed above in order to secure the most favorable conditions for the intelligibility of speech (G-75). This means that an optimum shape and size of the room, an adequate and correctly directed supply of short-delayed sound reflections, the provision for the required short R.T., full elimination of possible acoustical defects, reasonable noise control, etc., should all be carefully considered and secured. The optical and acoustical requirements in Lecture Halls are in complete agreement: suitable room proportion and shape will contribute equally to good sight and good hearing.

The exact purpose of a Lecture Hall should be ascertained and clarified well in advance because rooms to be used for demonstration purposes or for audio-visual education (G-74, G-86) will require particular care in their acoustical design and detailing.

In the interest of exterior noise exclusion, contemporary Lecture Halls are seldom designed with natural light and ventilation. This will necessitate the design of a complex ceiling incorporating various mechanical and lighting components, necessarily creating acoustical problems in the design of the sound reflective ceiling (G-77, G-79, G-80, G-83, G-84, G-85, G-89).

In the R.T. calculation of Lecture Halls it is customary to assume about two thirds of the capacity audience.

Lecture Halls with volumes of up to about 50,000 ft^3, or for an audience of up to about 500, will not require a sound amplification system if their acoustical design is based on the principles and recommendations discussed so far. Figure G.5

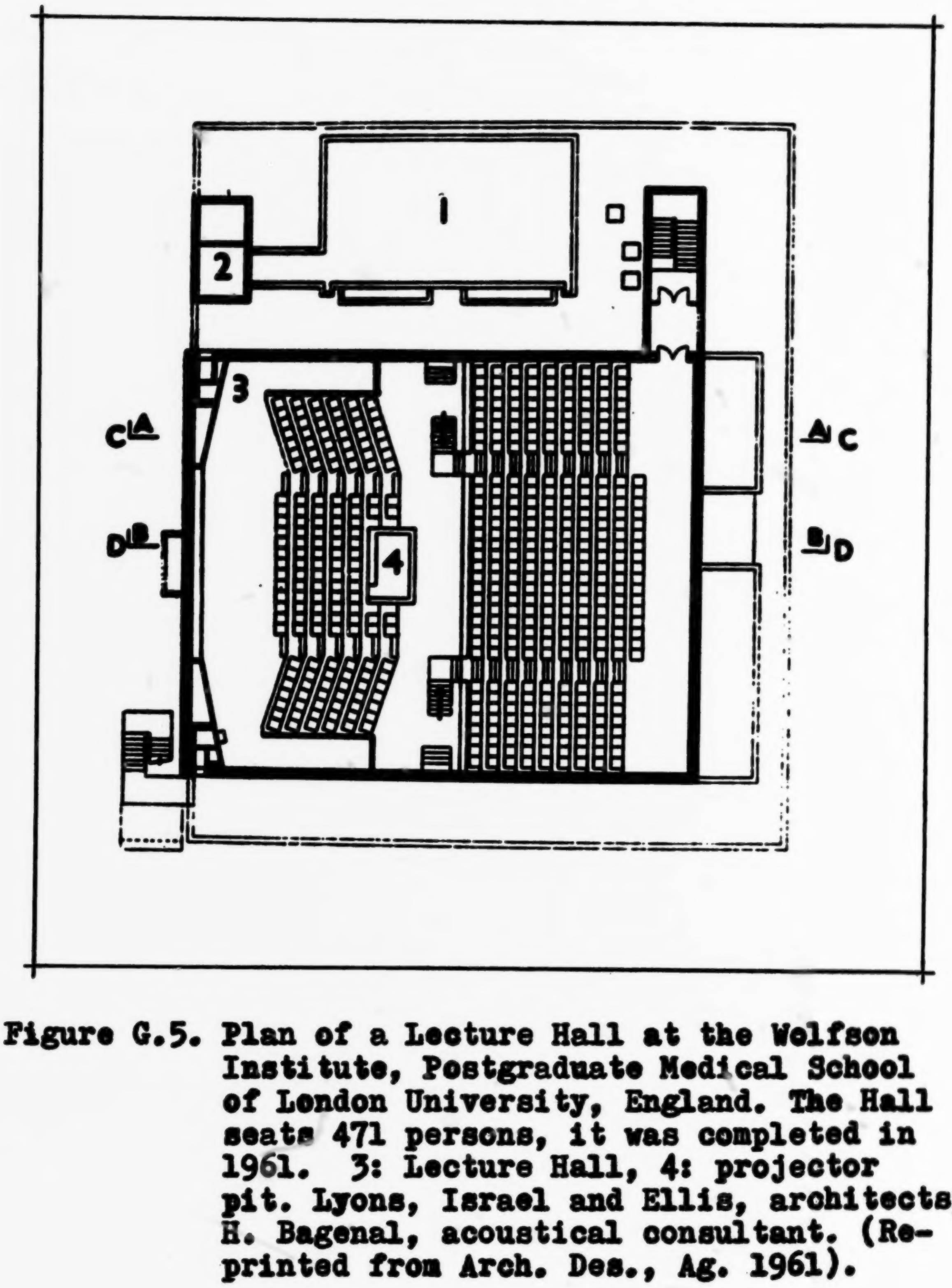


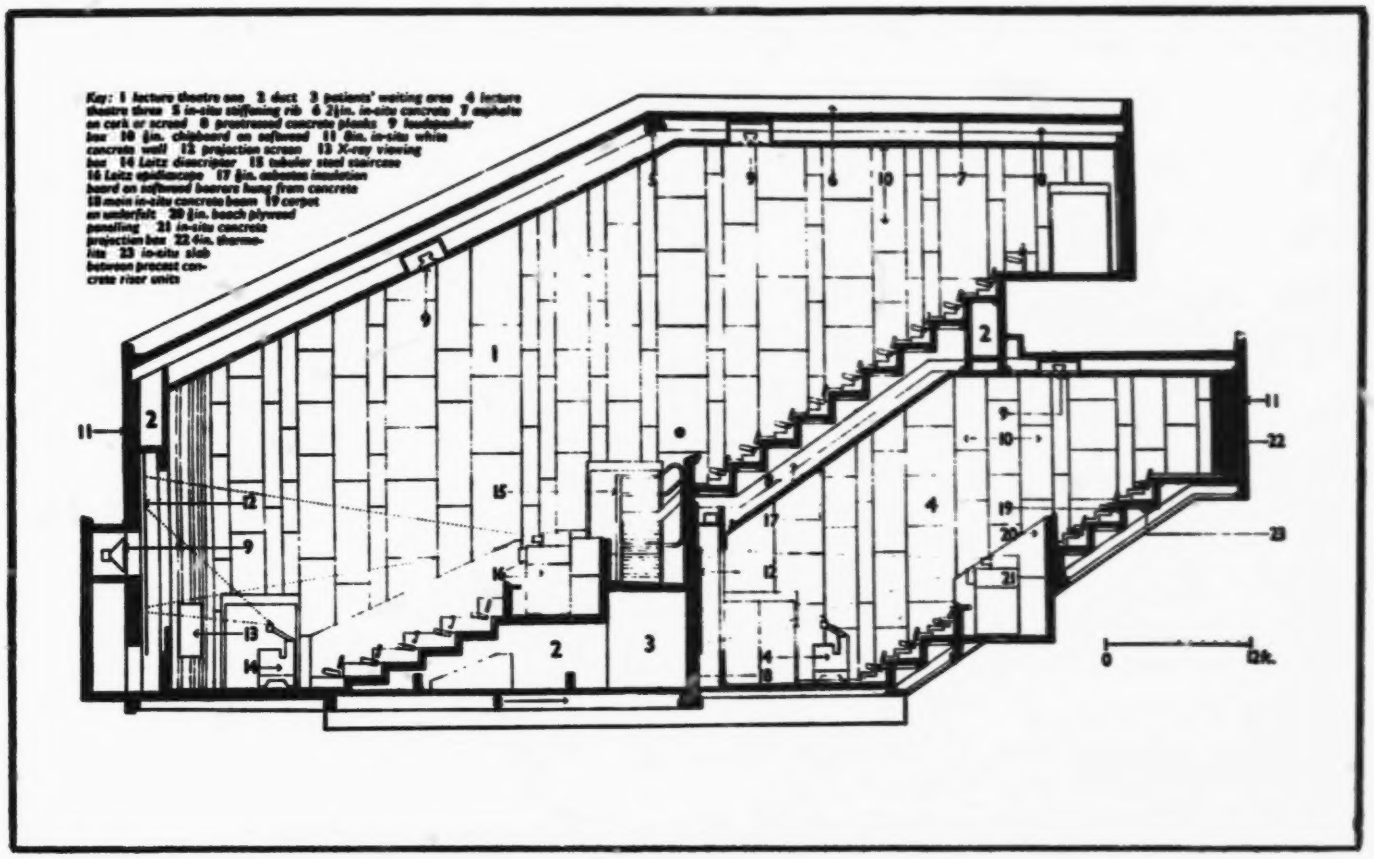
Figure G.5. Plan of a Lecture Hall at the Wolfson Institute, Postgraduate Medical School of London University, England. The Hall seats 471 persons, it was completed in 1961. 3: Lecture Hall, 4: projector pit. Lyons, Israel and Ellis, architects; H. Bagenal, acoustical consultant. (Reprinted from Arch. Des., Ag. 1961).

and Figure G.6 illustrate the plan and section of an exemplary Lecture Hall at the Wolfson Institute, London, England (G-84).

Classrooms with rectangular shapes and level floors, their floor areas normally varying between about 600 and 1000 ft^2, and their volumes between about 6000 and 12,000 ft^3, seldom create any serious acoustical problem (G-75). The rear wall, opposite the lecturer, even if acoustically untreated, will seldom cause any audible acoustical defect (such as echo, long-delayed reflection) because the length of the Classroom is small and the usually installed pin-up boards, wall tables, built-in book shelves and cupboards will dissipate and diffuse incident sound.

The R.T. of the Classrooms should be approximately 0.6 to 0.9 sec at the midfrequency when full, depending on their volume (G-74, G-78, G-81, G-89). This requirement is mostly fulfilled if the rooms are occupied, well furnished with built-in accessories (shelves, cupboards, etc.), and if light-weight, prefabricated building panels (plaster boards, drywall construction, suspended ceiling, etc.), large glazed areas, luminous fixtures, etc., are installed in the Classroom. If the application of additional absorbent treatment seems to be necessary, this should be installed along the edges of the ceiling or on the upper parts of the side and rear walls (G-3, G-81, G-89, GB-52). No matter how much additional absorbent finishes are required in the Classroom, the middle portion of the ceiling should always be kept reflective to provide uniform sound energy distribution, originating from any part of the room (G-81, G-87).

The noise control of Lecture Halls and Classrooms, a requirement of importance, will be dealt with in Section S.


Key: 1 lecture theatre one 2 duct 3 patients' waiting area 4 lecture theatre three 5 in-situ stiffening rib 6 2½in. in-situ concrete 7 asphalte on cork or screed 8 prestressed concrete planks 9 loudspeaker box 10 ⅝in. chipboard on softwood 11 8in. in-situ white concrete wall 12 projection screen 13 X-ray viewing box 14 Leitz diascripter 15 tubular steel staircase 16 Leitz epidiascope 17 ⅝in. asbestos insulation board on softwood bearers hung from concrete 18 main in-situ concrete beam 19 carpet on underfelt 20 ⅝in. beech plywood panelling 21 in-situ concrete projection box 22 4in. thermo-lite 23 in-situ slab between precast concrete riser units
1
2
3
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5
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11
12
13
14
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16
17
19
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21
22
23
0
12ft.

Figure G.6. Section of the Lecture Hall shown in Figure G.5. (Reprinted from Arch. Des., Ag. 1961).

G.4.3 Assembly Halls, Congress Halls

This paragraph reviews Assembly Halls of educational buildings or of other large establishments (Office, Factory), and Congress Halls in which precedence is given to sound programs, such as lectures, plays performed by amateur groups, panel discussions, debates, vocational or political meetings, congresses, etc., and which require primarily the intelligibility of the spoken word. These Auditoria, although constructed without stage facilities and equipment, are occasionally used for musical programs and film projections. Usually housing an audience of considerable number, they should always be equipped with a speech reinforcement system.

In their acoustical design, besides considering the principles described so far, particular attention should be paid to the following points (G-90, G-92, G-98, G-99, H-104):

(a) compact room shape and size,
(b) natural reinforcement of direct sound energy supply,
(c) ample distribution of direct sound,
(d) sound diffusion by wall and ceiling irregularities,
(e) reasonable compromise in R.T., close to speech requirements,
(f) heavily·upholstered seats,
(g) carpeted aisles,
(h) acoustically treated rear wall in case of danger of harmful reflections,
(i) removable orchestra shell, adjustable in size,
(j) high quality speech reinforcement system, providing uniform coverage with amplified sound,
(k) exclusion of exterior noise, provision for low background noise.

Figure G.7 illustrates an Assembly Hall, and Figure G.8 shows a Congress Hall (G-90, G-91, G-93, G-94, G-95, G-96, G-97, G-100, G-101, G-102, G-103, G-105).

G.4.4 Conference Rooms, Court Rooms, Chambers for Local and National Government

From an acoustical point of view, Auditoria in which administrative, debating, judicial and legislative activities take place, have the following acoustical requirements in common (G-3, G-107):

- the provision for high intelligibility of speech must receive top priority, and
- good hearing conditions are required for sources of speech sound originating from many different positions in the room.

The requirement for a low volume per seat value, recommended at 100 to 175 ft^3 in paragraph G.3, unfortunately conflicts with aesthetic aspects aiming at a dignified and impressive interior in many of these Auditoria. For Conference Rooms and Court Rooms, because of their relatively lower ceiling heights, the achievement of a volume per seat figure of about 100 to 150 ft^3 is feasible; in Parliament Chambers, however, this figure will often reach the 350-400 ft^3 value at capacity attendance; it may raise to as high as 1000 ft^3 in case of low attendance, not infrequent in the history of Legislative Assemblies. Under such conditions a very poor speech intelligibility can be expected.

Seating arrangements will obviously vary according to architectural layout, capacity and purpose of the room, however, potential speaking members of the participating audience should face each other, within the limits of possibility. Since semicircular and horseshoe shaped floor areas will best meet this requirement, attention should be given to the elimination of

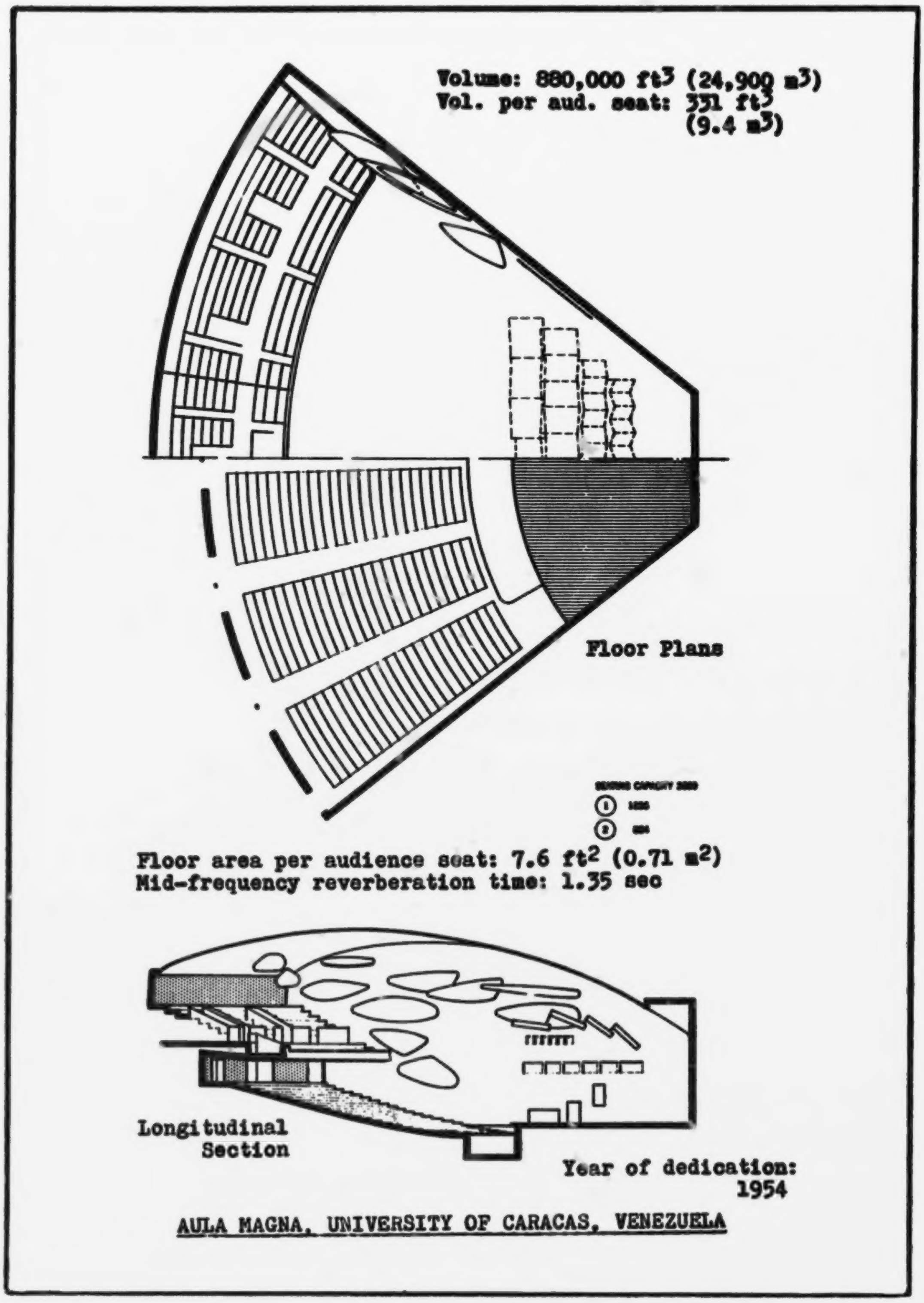
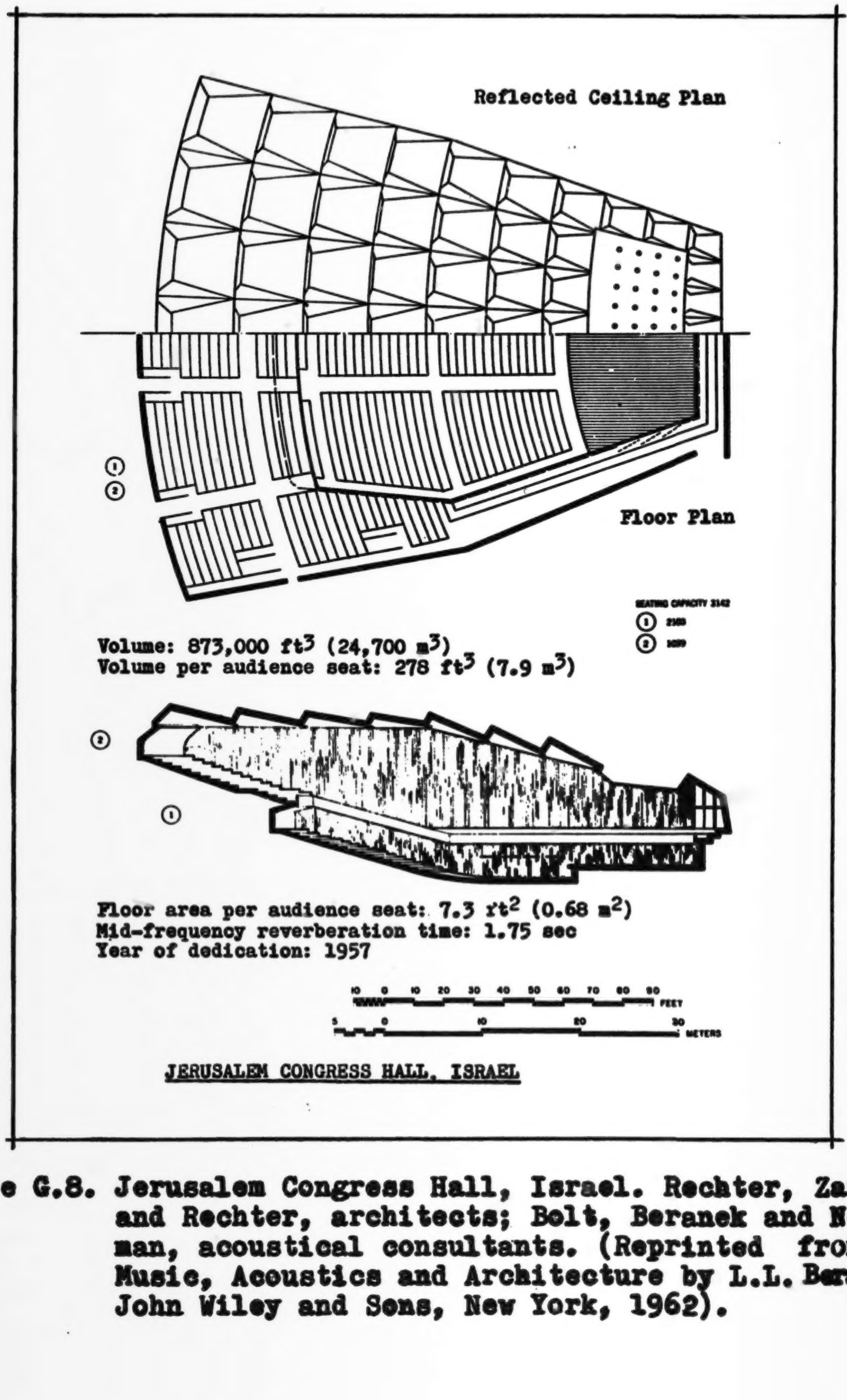

Volume: 880,000 ft^3 (24,900 m^3)
Vol. per aud. seat: 331 ft^3 (9.4 m^3)
Floor Plans
SEATING CAPACITY
①
②
Floor area per audience seat: 7.6 ft^2 (0.71 m^2)
Mid-frequency reverberation time: 1.35 sec
Longitudinal Section
Year of dedication: 1954
AULA MAGNA, UNIVERSITY OF CARACAS, VENEZUELA

Figure G.7. Assembly Hall of the University of Caracas, Venezuela. C.R. Villanueva, architect; Bolt, Beranek and Newman, acoustical consultants. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).


Reflected Ceiling Plan
①
②
Floor Plan
SEATING CAPACITY 3142
① 2103
② 1039
②
①
10 0 10 20 30 40 50 60 70 80 90 FEET
5 0 10 20 30 METERS

Volume: 873,000 ft^3 (24,700 m^3)
Volume per audience seat: 278 ft^3 (7.9 m^3)

Floor area per audience seat: 7.3 ft^2 (0.68 m^2)
Mid-frequency reverberation time: 1.75 sec
Year of dedication: 1957

JERUSALEM CONGRESS HALL, ISRAEL

Figure G.8. Jerusalem Congress Hall, Israel. Rechter, Zarhy and Rechter, architects; Bolt, Beranek and Newman, acoustical consultants. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

back-reflections and sound concentrations from curved boundary surfaces.

The following items should be checked, in addition to those dealt with in preceding paragraphs, during the acoustical design of Conference Rooms, Court Rooms, and Chambers for Local or National Government (G-3, G-107, G-111, GB-52, GB-53):

(a) greatest economy in floor area and volume,
(b) minimum ceiling height,
(c) reflective and dispersive ceiling treatment,
(d) steeply tiered seating and raised dais,
(e) short R.T. as required in Auditoria for speech,
(f) soft floor finish, particularly along the aisles,
(g) fixed and well absorbent (upholstered) seating,
(h) selection of a high quality speech reinforcement system if this is required by the room volume,
(i) exclusion of exterior noise, in view of the fact that these Auditoria are usually located in the noisiest districts of the city,
(j) achievement of low background noise level (see also Section M) if no sound amplification system will be used.

If these Auditoria are provided with space for public attendance, this should take the form of a secluded seating area (e.g., gallery), suitably separated from the main floor area. This public area should be treated acoustically as "dead" as possible with highly absorbing acoustical finishes, carpeted floors,and upholstered seats (G-108, G-109, G-110, G-111, G-112, G-113, G-114).

Figure G.9 shows the floor plans of three Council Chambers located in the Conference Building of the UN Headquarters, in New York.

Figure G.10 illustrates the floor plan of the Municipal Council Chamber in the City Hall of Yaita, Japan (G-114).

Three council chambers (plan below) are directly above three conference rooms (section above). Conference Building is link between Secretariat (below) and General Assembly Building (right).

THIRD FLOOR

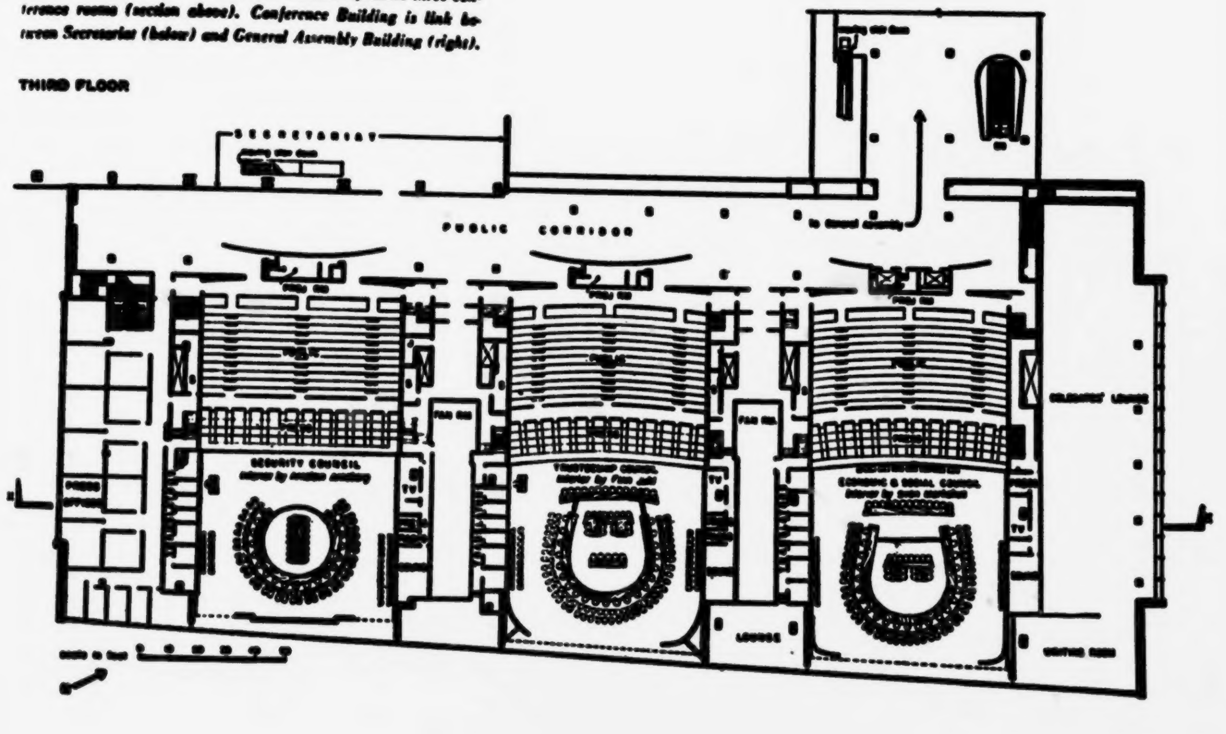

SECRETARIAT
PUBLIC CORRIDOR
SECURITY COUNCIL
TRUSTEESHIP COUNCIL
ECONOMIC & SOCIAL COUNCIL
LOUNGE
WAITING ROOM

Figure G.9. Plan of three Council Chambers in the United Nations Building, New York. A. Arneberg, F. Juhl, and S. Markelius, architects. (Reprinted from Arch. Forum, Ap. 1952).

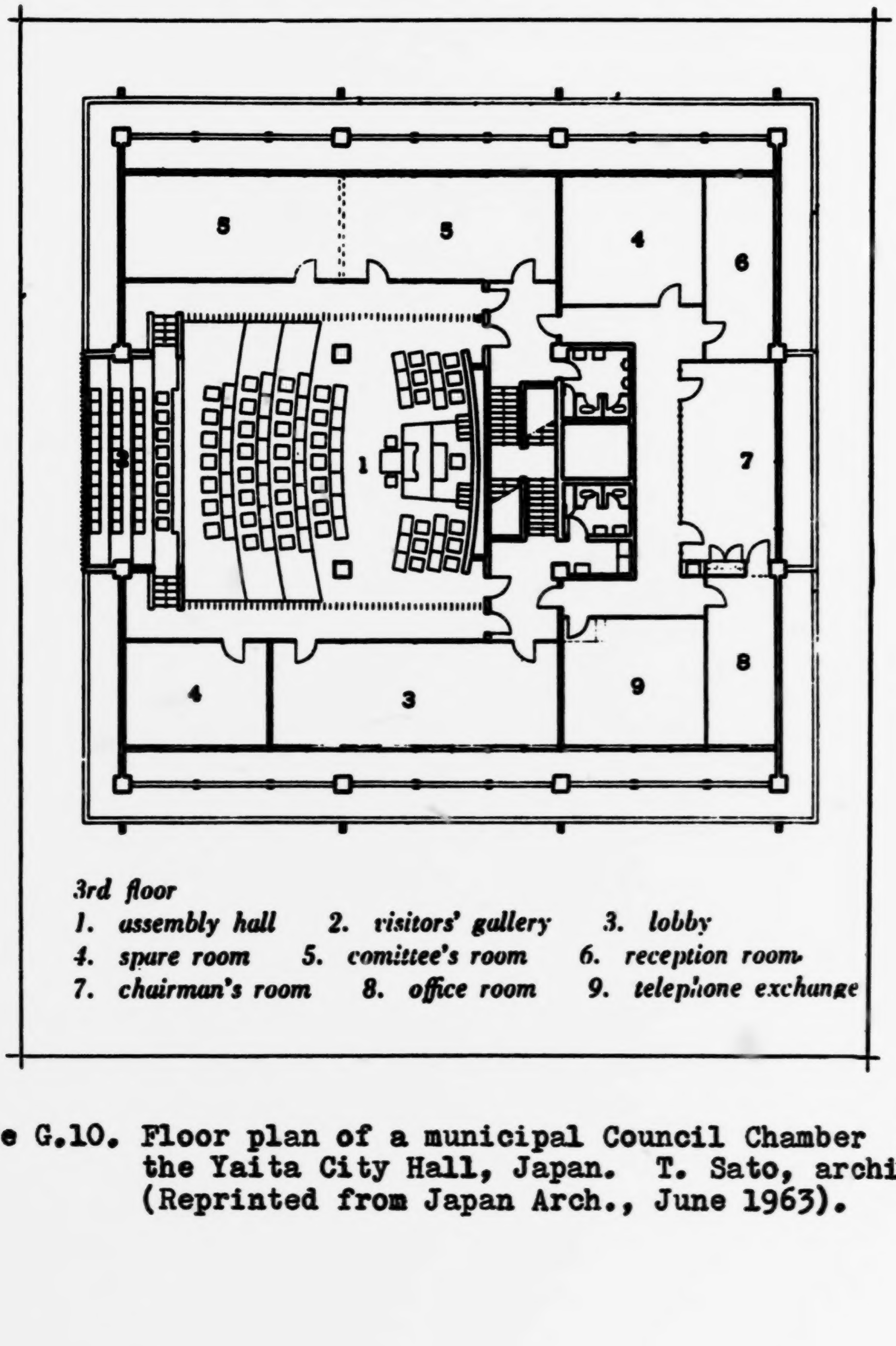

5
5
4
6
1
2
7
4
3
9
8
3rd floor
1. assembly hall
2. visitors' gallery
3. lobby
4. spare room
5. comittee's room
6. reception room
7. chairman's room
8. office room
9. telephone exchange

Figure G.10. Floor plan of a municipal Council Chamber in the Yaita City Hall, Japan. T. Sato, architect. (Reprinted from Japan Arch., June 1963).

G.4.5 Gymnasia, Arenas, Swimming Pools, Bowling Alleys

The activities taking place in these Auditoria are often serious noise producers; this will disturb not only the participants and spectators within the Halls (Gymnasia, Swimming Pools, Bowling Alleys), but constitute objectionable sources of interference to near-by rooms as well (G-2, G-115). The acoustical finishes used in these Auditoria, therefore, should serve two purposes: they should contribute to a short R.T., and they should reduce at the same time the prevailing noise level.

Acoustical finishes installed in Auditoria will contribute to noise reduction within the Auditoria only, and will not prevent the penetration of noise into adjacent areas; the problem of noise insulation must be resolved independently. This might be achieved either by surrounding the noisy Auditorium with barriers that will provide adequate isolation against noise and vibration generated in the Auditorium; or by locating the noisy Auditorium as far as possible from rooms requiring quiet acoustical environment. This will be dealt with in Section M.

Because of functional requirements, opposite boundary surfaces of these Auditoria are generally parallel, often giving rise to harmful acoustical phenomena, such as excessive reverberation and flutter echoes. Since a marked deviation from the rectangular room shape is seldom justified in these Auditoria, the proper distribution of sound absorbing materials and the abundant application of surface irregularities (exposed structural elements, recesses, splays, serrations, etc.) is imperative (GB-21).

Acoustical finishes applied in some of the Auditoria classified under this group have to resist mechanical impacts (in Gymnasia), and also withstand humidity (in Swimming Pools) (G-126, G-129, G-130). The choice of acoustical materials in Auditoria has been reviewed in paragraph E.8.

Huge arena-type Auditoria are frequently constructed to be used for a wide range of programs and to accommodate a vast audience (G-116, G-117, G-123, G-125, G-131). In such cases, various, often conflicting, acoustical requirements have to be blended into a single concept, resulting in a reasonable compromise only at best.

Figure G.11 illustrates details of the huge Vienna Sports Hall, in Austria, which is used satisfactorily for stage performances, skating rink, film projections, cycling competitions, tennis championships and prize fighting, with a different seating arrangement for each particular program. The audience capacity of this Arena can be varied between 2000 and 16,000 (G-121, G-122, G-124, G-127, G-128).

These huge Auditoria are far too large to provide satisfactory hearing conditions by natural sound. The installation of a sound amplification system that will produce uniform coverage and naturalness in every part of the seating area is therefore indispensable.

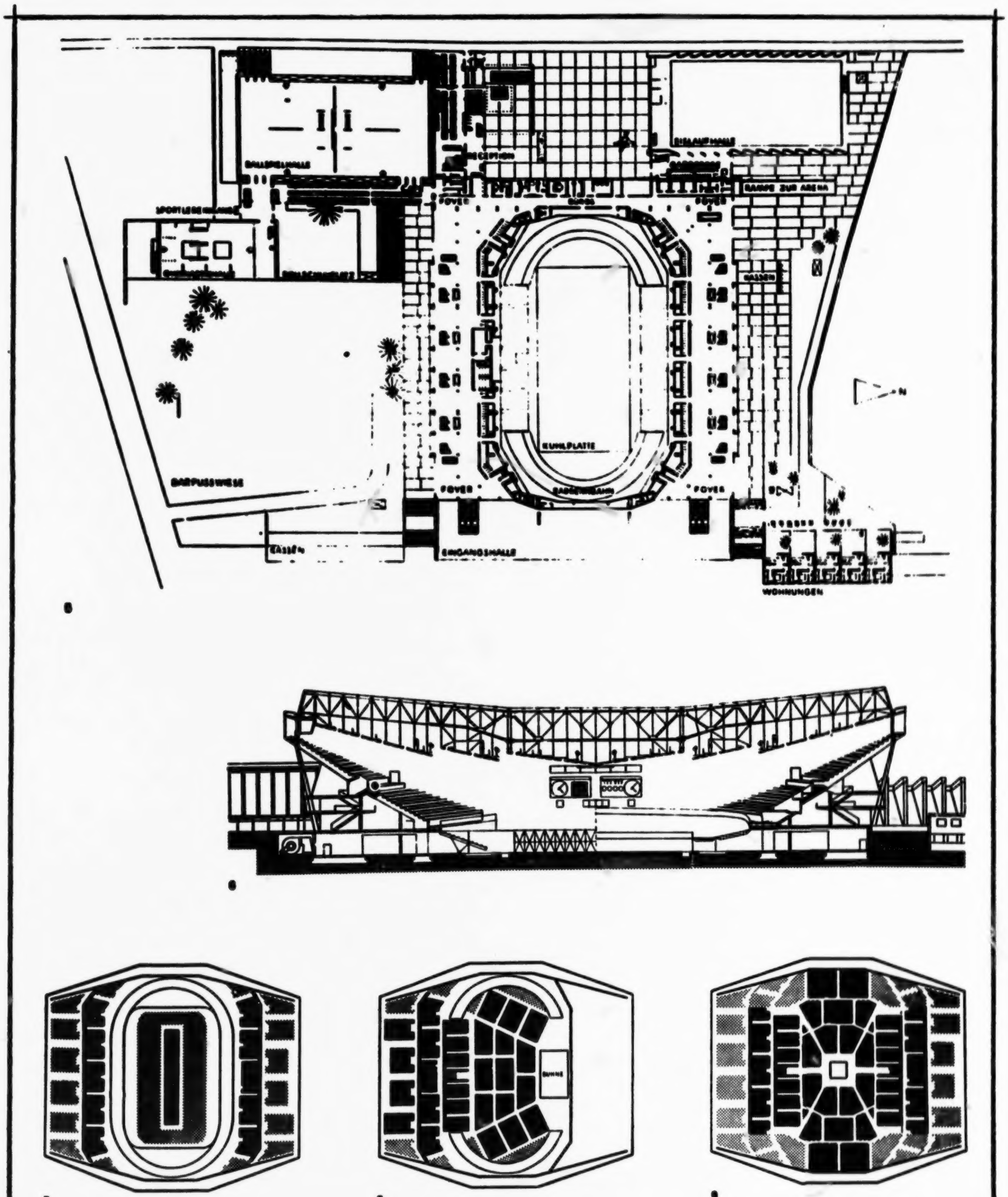

FOYER
KÜHLPLATTE
KASSEN
EINGANGSHALLE
WOHNUNGEN
BÜHNE
7
8
9

Figure G.11. The Vienna Sports Hall with a variable audience capacity of 2000 to 16,000, completed in 1958. Top: ground floor plan, middle: cross section, bottom (from left): the Hall set up for cycling competitions, the Hall transformed into a regular Theater, the Hall set up for prize-fighting. R. Rainer, architect; E. Skudrzyk and E. Hirschwehr, acoustical consultants. (Reprinted from Werk, No.3, 1959).

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(See list of abbreviations on page 1)

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Section H. Acoustical design of Rooms for Music

- H.1 Room acoustical attributes related to the quality of music
- H.2 Effect of room acoustical attributes on music
  - H.2.1 Effect on composition
  - H.2.2 Effect on performance
  - H.2.3 Effect on listening
- H.3 Special considerations in the architectural-acoustical design of Auditoria for music
- H.4 Auditoria for music
  - H.4.1 Concert Halls
  - H.4.2 Opera Houses
  - H.4.3 Music Rooms, Rehearsal Rooms
- References

While the acoustical efficiency of rooms for speech can be measured by objective speech intelligibility tests (G-1, G-2, G-3), the methods available for the acoustical evaluation of Auditoria for music are mostly subjective. These subjective methods, based on the judgement of individuals (musicians, performers, conductors, music critics and concert-goers), have been tried and tested over the years and have culminated in a rather complete checklist, compiled by L.L. Beranek, against which the musical-acoustical quality of an Auditorium can be compared and evaluated with reasonable accuracy (H-6).

H.1 Room acoustical attributes related to the quality of music

The following are the room acoustical attributes which have an effect on the quality of music (H-3, H-5, H-6, H-7, H-8, H-19):

(A) Acoustical intimacy or presence. An Auditorium has acoustical intimacy if music played in it gives the impression that it is being performed in an intimate, small room. Usually it is not possible, nor is it necessary, for the Auditorium to be limited to this particular size,but only that it sound as though it were of this size. The degree of acoustical intimacy of an Auditorium will depend on the initial-time-delay gap, i.e., the time interval between direct sound received by a listener and the first reflection from any boundary surface of the room. If the initial-time-delay gap in a room is shorter than 20 milliseconds (20 one-thousandths of a second), corresponding to a path difference of 23 ft, and the direct sound is not too faint, the room will be found to be acoustically intimate. Acoustical intimacy is probably the most outstanding acoustical feature that an Auditorium, used primarily for music, can possess.

(B) **Liveness.** An Auditorium will be live if it has a large volume relative to its audience capacity, with predominant sound reflective enclosures. A live hall has a relatively long R.T., particularly at the middle and high frequencies, resulting in a full, sustained tone at this frequency range.

(C) **Warmth.** Music has the quality of warmth when it has a fullness of the bass tone relative to that of the mid-frequency and high frequency tones. This will be noticeable when the reverberation times of the low frequency sounds (250 cps and below) are longer than those of the middle and high frequency sounds, resulting in a rich bass.

If the R.T. is adequately controlled over the entire audio-frequency range, a **fullness of tone** will be noticeable. Excessive fullness of tone in a room makes the sound muddy, blurred and unenjoyable.

(D) **Loudness of direct sound.** In a small Auditorium, the audience, even when located in the remotest seats, will always receive an adequate amount of direct sound. In large halls, however, the seats must be steeply ramped, and the sound source must be well elevated, in order to provide a sufficient amount of direct sound for the remote seats.

(E) **Loudness of reverberant sound.** This will depend on two factors: the intensity of the reflected sounds and R.T. (with capacity audience). There must be an appropriate balance between room volume and R.T. in order to provide a satisfactory loudness for the reverberant sound (Figure F.3).

(F) Definition or clarity. If the sounds of the various musical instruments, played simultaneously in an orchestra, are easily distinguished and if every note within a rapid passage is heard separately, the room possesses definition or clarity. Good definition will prevail if (a) a considerable amount of short-time-delayed reflections have been provided for (i.e., the hall has intimacy), (b) if the room has a relatively small volume with a short R.T., and (c) if the listeners are close enough to the sound source (i.e., the ratio of direct to reverberant sound is relatively large).

Definition and fullness of tone are normally inversely related, i.e., a room possessing a high degree of definition will usually have a short R.T. and vice versa.

(G) Brilliance. This will occur when there is an abundance of bright and clear high frequency sounds. It will be more pronounced if the room has a considerable amount of reflective surfaces, if it has liveness and if the listeners are close enough to the sound source. If the Auditorium has acoustical intimacy, liveness and definition, it will certainly have brilliance.

(H) Diffusion. If reflected sound waves approach the listeners from every direction in approximately equal amounts, diffusion will be observed in the room. A relatively long R.T. and ample wall and surface irregularities will promote diffusion.

(I) Balance. The control of this attribute is partly in the hands of the conductor. Suitably proportioned reflective and diffusive surfaces around the sound source will strengthen and improve both kinds of balance, i.e., (1) between sections of the orchestra, and (2) between musicians and soloists.

(J) **Blend**. If musical sounds are well mixed together before they reach the listeners, so that they are perceived as harmonious, the "sending end" of the Auditorium has a good blend. The reflective and diffusive orchestra enclosures control blend. An orchestra platform or orchestra pit will not have a good blend if it is too wide.

(K) **Ensemble**. This is the capability of the musicians and soloists to perform in unison so that the entire orchestra sounds as a well rehearsed and coordinated unit. Undoubtedly.ensemble is controlled primarily by the conductor, however, it will also be enhanced by a well proportioned and suitably raked stage floor and also if the stage enclosures will readily project the sounds from one side of the platform to the other.

(L) **Immediacy of response (or attack)**. The quality of an Auditorium such that it responds instantly to the sounds of the performers is termed as immediacy of response, or attack. This will be achieved by the following room acoustical phenomena: (a) the periodical return of back reflections from the audience area to the performers; (b) the projection of short-delayed first reflections toward the seating area; (c) properly controlled R.T. (subsection F.5); (d) good diffusion; (e) suitably proportioned platform area with ensemble-promoting reflective enclosures; (f) the absence of echoes and long-delayed reflections.

(M) **Texture**. The pattern of sound reflections perceived by the listeners in a room, superimposed on the general impression of the performance, is called texture. This is beneficial in a room if later sound reflections follow uniformly the short-delayed first reflections.

(N) Freedom from echo. The elimination of echoesfrom every Auditorium, discussed in subsection F.6, is of unquestionable importance.

(O) Freedom from noise. The elimination or reduction of exterior noise (due to traffic, ventilating or air-conditioning systems, machinery, etc.) to inaudibility and the reduction of interior noise to an acceptable minimum is one of the most important requisites of an Auditorium for music.

(P) Dynamic range. This is the spread of the audible sounds within a room, extending from a normal low level of noise created by the audience to the loudest tones produced by the orchestra. The loudest sounds should not reach a level that would cause discomfort to the auditors.

(R) Tonal quality. Similar to a fine musical instrument, an Auditorium can also have a beautiful tonal quality. Considerable damage can be afflicted upon the tonal quality of a room by the creaking of doors, rattles caused by inadequately joined or fastened surfaces, the uneven or excessive absorption of materials, flutter echoes, coloration, etc.

(S) Uniformity. Uniformity of sound over the entire audience and performing area is one of the finest room acoustical qualities an Auditorium can possess. Rather few halls exist which are entirely devoid of seats (often entire rows) of poor hearing conditions, relative to other seats. Listening conditions can be comparatively poor (a) at the extreme side seats of the front rows in a disproportionately wide hall, (b) under an excessively deep balcony overhang, and (c) at locations receiving overly long-delayed reflections, slap-backs, echoes, etc. Absence of uniformity of sound can be particularly noticeable in very large Auditoria with an audience capacity above about 2500.

H.2 Effect of room acoustical attributes on music

Room acoustical attributes exercise a marked influence on the various stages of the musical process, i.e., on composition, on performance (production) and on listening (H-5, H-6, H-9, H-12, H-13, H-14, H-15, H-109).

H.2.1 Effect on composition

As already outlined in Section B, "History of Architectural Acoustics", the music of early composers was largely influenced by the acoustical setting of the room in which their work was written or performed.

Composers of Church music, throughout the centuries, have never failed to exploit the beneficial effect of fullness of tone upon their music, a room acoustical feature characteristic of Church Auditoria.

Baroque and classical music was scaled to relatively small, rectangular Halls, Ballrooms, or Theaters. These rooms were of moderate size, they had reflective enclosures producing a high degree of acoustical intimacy with short R.T. and excellent definition, ideal for baroque and classical music.

Composers of the Mozartian or European operas (Rossini, Donizetti, Verdi, etc.) envisaged the Italian-type Opera Houses when composing their operas which required a high degree of definition, and a relatively short R.T.

When composers of the romantic period conceived their symphonies and Wagner wrote his operas, they all composed for Auditoria that possessed remarkable intimacy, fullness of tone and a wide dynamic range (H-6).

Since the beginning of the present century music is no longer composed in terms of room acoustical qualities of existing Halls. In fact, Auditoria of our times have to satisfy an ever increasing number of musical-acoustical requirements in order to provide an optimum sonic environment for the performance of music.

H.2.2 Effect on performance

Since the appreciation of music can never be dissociated from the acoustical environment of the room in which it is presented, musicians or soloists normally find it desirable to adjust their performance to the acoustical qualities of the Auditorium in which they perform. They are fully aware that their success does not depend solely on their personal artistic talent but to a great extent on several positive acoustical features of the room. Before selecting a tempo for their performance that they interpret as being in accordance with the composer's intent, they will have to check on prevailing room acoustical features; such as, intimacy, fullness of tone, definition, brilliance, diffusion, attack, tonal quality, etc. (H-16). Rehearsals also serve the purpose of familiarizing the performers with important musical-acoustical qualities of the Auditorium. These room acoustical characteristics will reward the performers when fully respected, but they can foster a failure when disregarded. Conductors will always adjust the style and technique of their performance according to the acoustical characteristics of the hall in question.

H.2.3 Effect on listening

It remains to the audience and the music critic to say the final word in accepting or refusing the work of a composer or a performance. Both the audience and the music critic will be influenced greatly by the acoustical qualities of the Auditorium in their evaluation of a musical performance; (a) in their approval or disapproval of the music, and (b) in deciding whether or not they consider the hall in which they listened suitable for the performance of music.

Naturally the selection of the program of a concert and the number of performers engaged simultaneously in the program always depend on the basic acoustical attributes of the hall selected for the concert. No conductor would ever think of presenting. Bach's Brandenburg Concertos in a highly reverberant Auditorium, or to interpret Brahms in a "dead" hall.

Extensive research work is being done continuously to discover and evaluate the audience's preferences as to the optimum acoustical environment for listening to music of various periods and styles. An important investigation of this kind was carried out by W. Kuhl (J-71, J-72). As a conclusion of his large-scale tests, competent listeners showed an almost unanimous preference for the following reverberation times for the various styles of music (at mid-frequency):

- for classical music (e.g., Mozart's Jupiter Symphony) about 1.5 sec;
- for romantic music (e.g., Brahm's Fourth Symphony) 2.1 sec; and
- for modern music (e.g., Stravinsky's Le Sacre du Printemps) about 1.5 sec.

These values of the preferred reverberation times (plotted in Figure F.3,and shown in Figure J.1) were not dependent on the size of the room. Kuhl suggested that the most favorable compromise for various musical styles is a R.T. of 1.7 sec for rooms occupied by the audience and orchestra. The results of Kuhl's tests are in agreement with the findings of L.L. Beranek's well-documented study of 54 outstanding Auditoria (H-6).

Although the design of Auditoria is still based generally on tradition (H-5), the reaction of people to music provides us with important clues in the design of Auditoria for music.

H.3 Special considerations in the architectural-acoustical design of Auditoria for music

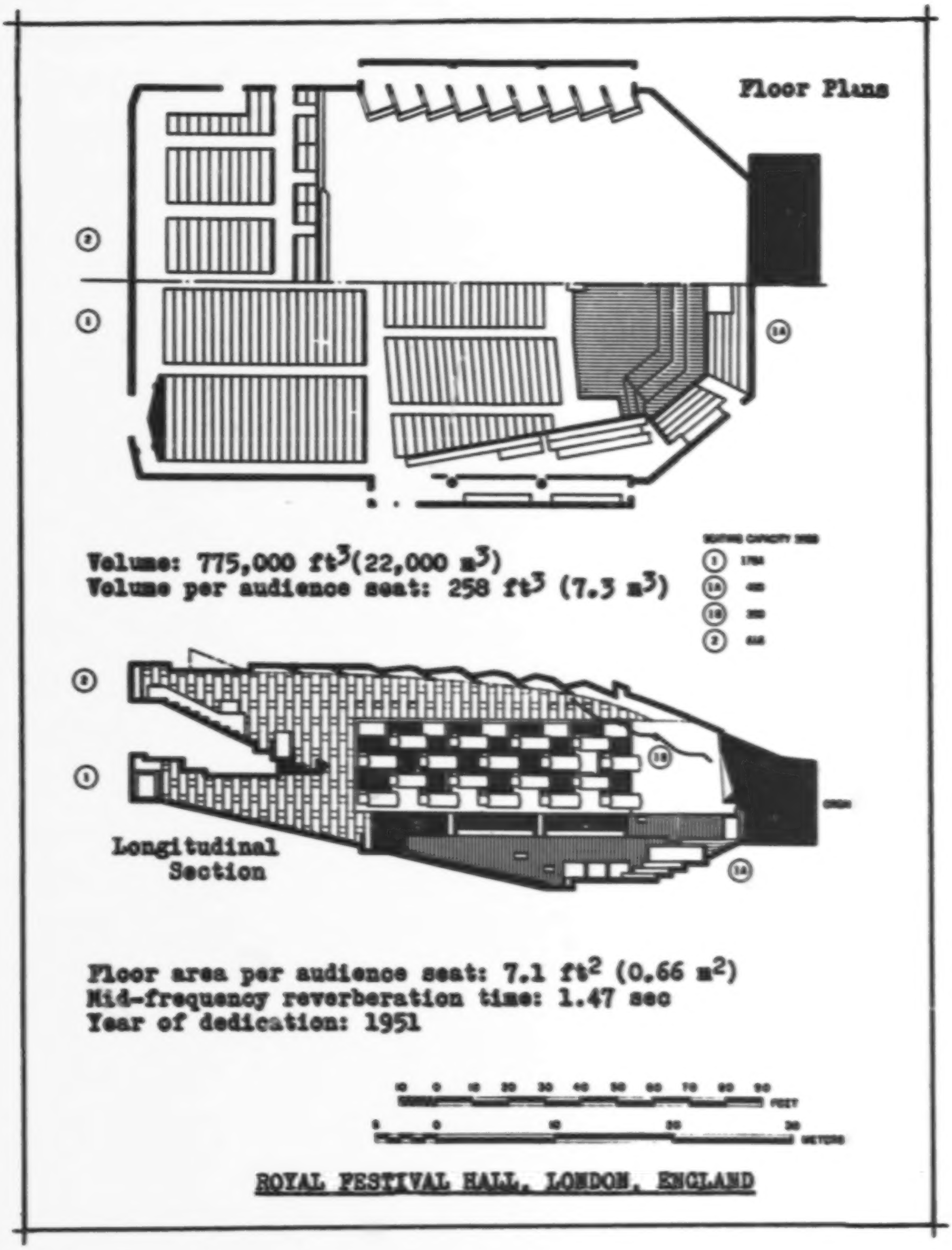
Since the architectural design of Auditoria for music has to satisfy an ever increasing, and often conflicting, range of aesthetical, functional, dimensional, structural, environmental, musical-acoustical, and - last but not least - financial requirements, relevant recommendations can be made only on a general level. This assertion is supported by the fact that the acoustical problems involved apply too often to Auditoria of unusual size and shape seldom encountered before (H-21, H-64, H-67, H-70).

From the point of view of floor shapes, Auditoria for music can be divided into the following six groups:

(A) Rectangular. This floor shape has a remarkable tradition. Cross reflections between parallel walls contribute to an increased fullness of tone (H-22, H-36, H-109) with a certain risk of flutter echo and coloration.

Figure H.1 illustrates the Royal Festival Hall, London, a contemporary example of an Auditorium with a rectangular shape (H-34, H-35, H-38, H-39, H-40, H-41, H-42, H-47, H-48, H-49, H-50, H-55, H-101, H-113). Other examples are: Symphony Hall, Boston (H-83); Grosser Musikvereinssaal, Vienna (H-88, H-110); Musikhochschule, Berlin (H-91); St. Andrew's Hall, Glasgow (H-33, H-48, H-98); and Concertgebouw, Amsterdam (H-104).

(B) Fan-shaped. This floor shape brings the audience closer to the sound source, enabling the construction of balconies where the balance is usually enhanced (GB-53). The curved rear wall with a curved balcony front, unless acoustically treated or dispersive, is liable to create long-delayed reflections, echoes or sound concentrations. Acoustical conditions under the balcony require special attention.


Floor Plans
②
①
⑭
②
①
⑱
⑭
Longitudinal Section
FEET
METERS
10 0 10 20 30 40 50 60 70 80 90
5 0 10 20 30

Volume: 775,000 ft^3 (22,000 m^3)
Volume per audience seat: 258 ft^3 (7.3 m^3)

Floor area per audience seat: 7.1 ft^2 (0.66 m^2)
Mid-frequency reverberation time: 1.47 sec
Year of dedication: 1951

ROYAL FESTIVAL HALL, LONDON, ENGLAND

Figure H.1. Rectangular Concert Hall. R.H. Matthew, chief architect; H. Bagenal, acoustical consultant, in collaboration with the Building Research Station, England. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

The F.R. Mann Concert Hall, shown in Figure H.2, is an example of a fan-shaped hall (H-63, H-103). Other examples are: Kleinhans Music Hall, Buffalo (H-84); Tanglewood Music Shed, Lenox, Mass. (H-74, H-85, H-122); and Liederhalle, Stuttgart, illustrated in Figure H.9 (H-57, H-63, H-95, H-112).

(C) Horseshoe shaped. This is the traditional shape for Opera Houses with rings of boxes one atop the other. It provides a relatively short R.T., suitable for the rapid passages of the European opera, but too short for orchestral performances.

Figure H.3 illustrates the Academy of Music, in Philadelphia, an example of the horseshoe shaped hall for music (H-6). Other examples are: Teatro alla Scala, Milan (H-120, H-121, H-137); Carnegie Hall, New York (H-86); Metropolitan Opera House, New York (H-131); Royal Opera House (Covent Garden), London (H-136); and Teatro Colon, Buenos Aires (H-132).

(D) Circular. This floor shape is normally associated with a dome roof with excessive height. Unless treated acoustically, the curved enclosures might create echoes, long-delayed reflections, and sound concentrations. This shape should be avoided by all possible means.

The Royal Albert Hall, London, gives an example of a circular Auditorium, noted for its several acoustical deficiencies (H-26, H-27, H-100); this is shown in Figure H.4.

(E) Irregular. This shape can bring the audience unusually close to the sound source; it will secure acoustical intimacy, definition and brilliance, since surfaces to produce short-delayed reflections can be easily integrated into the overall architectural design. The irregular layout offers

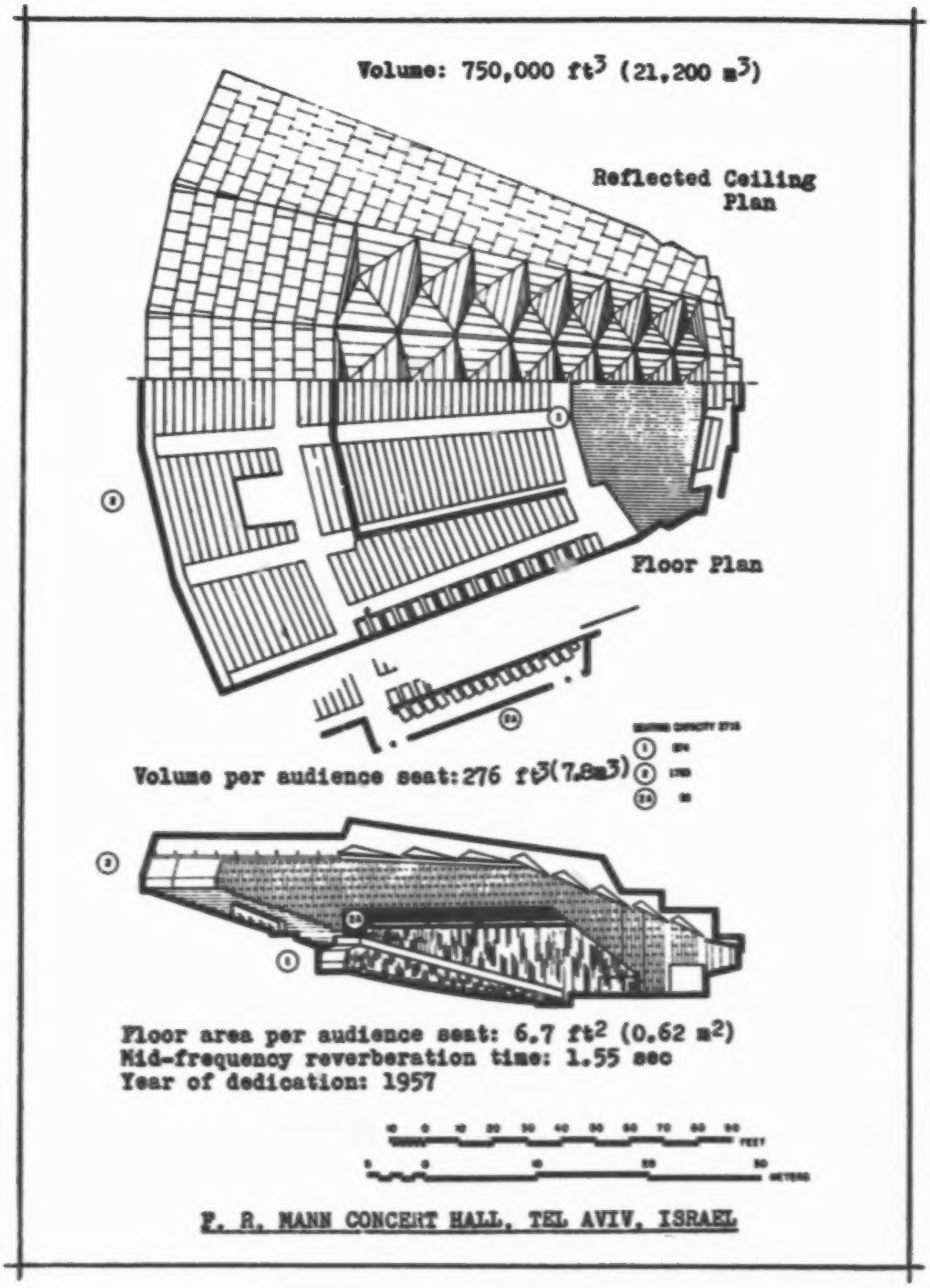
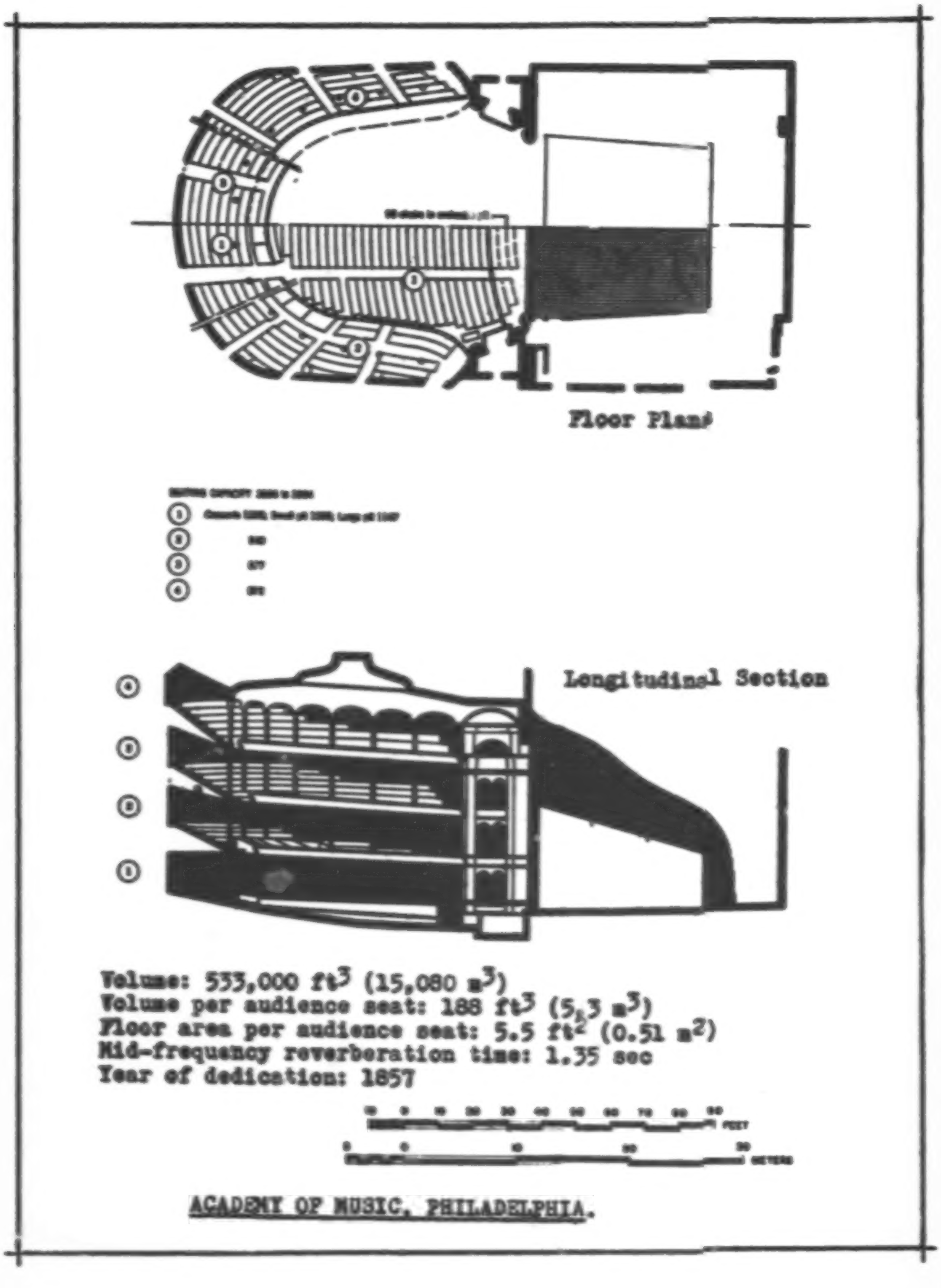

Volume: 750,000 ft³ (21,200 m³)
Reflected Ceiling Plan
Floor Plan
SEATING CAPACITY 2715
Volume per audience seat: 276 ft³ (7.8m³)
Floor area per audience seat: 6.7 ft² (0.62 m²)
Mid-frequency reverberation time: 1.55 sec
Year of dedication: 1957
FEET
METERS
F. R. MANN CONCERT HALL, TEL AVIV, ISRAEL

Figure H.2. Fan-shaped Concert Hall. Z.Rechter and D.Karmi, architects; Bolt, Beranek and Newman, acoustical consultants.(Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).



Volume: 533,000 ft^3 (15,080 m^3)
Volume per audience seat: 188 ft^3 (5.3 m^3)
Floor area per audience seat: 5.5 ft^2 (0.51 m^2)
Mid-frequency reverberation time: 1.35 sec
Year of dedication: 1857

ACADEMY OF MUSIC, PHILADELPHIA.

Figure H.3. Horseshoe shaped Auditorium for music. N.H.C. LeBrun and G. Runge, architects. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

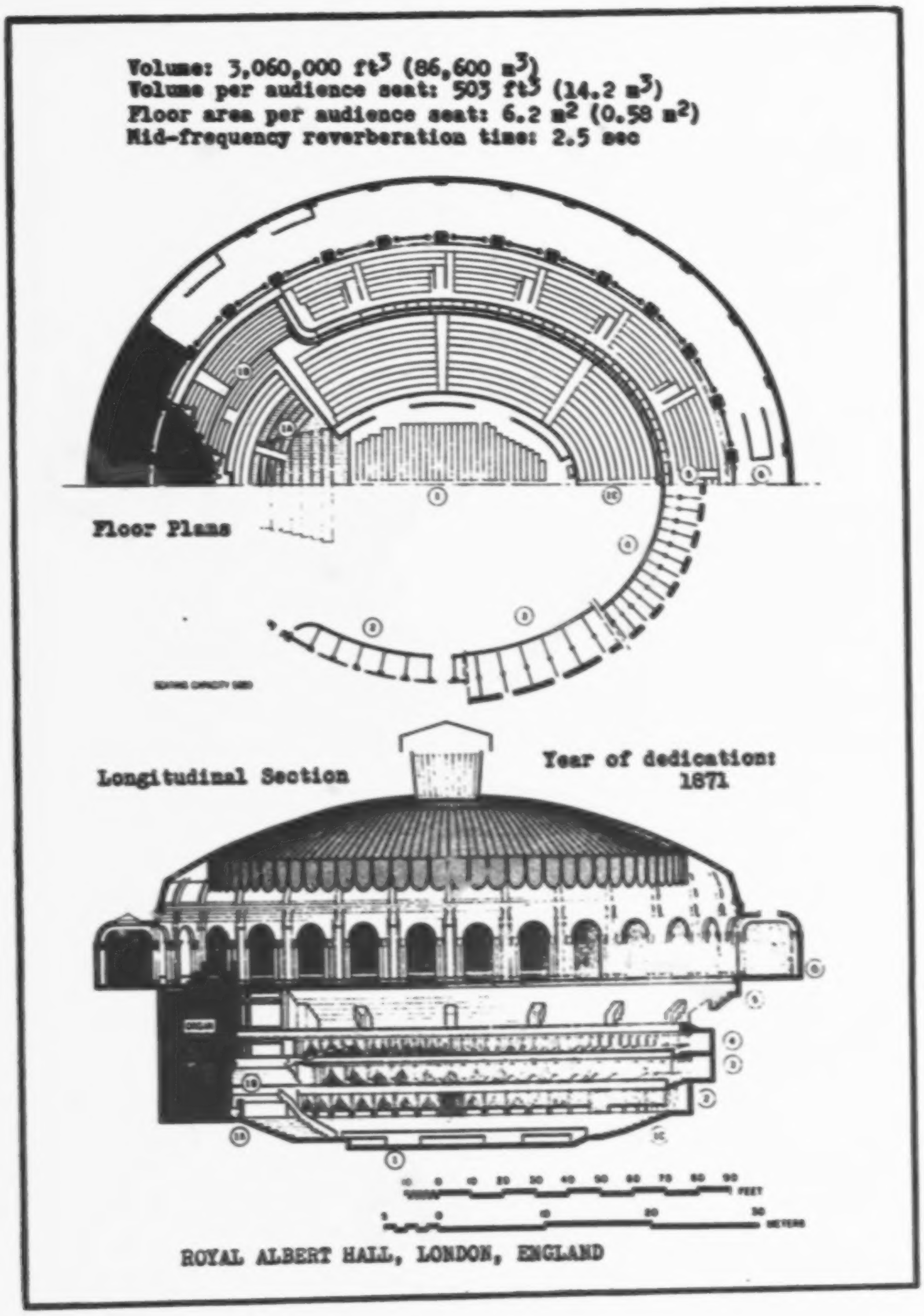

Volume: 3,060,000 ft^3 (86,600 m^3)
Volume per audience seat: 503 ft^3 (14.2 m^3)
Floor area per audience seat: 6.2 m^2 (0.58 m^2)
Mid-frequency reverberation time: 2.5 sec
Floor Plans
Longitudinal Section
Year of dedication: 1871
FEET
METERS
ROYAL ALBERT HALL, LONDON, ENGLAND

Figure H.4. Oval Concert Hall. F. Fowke and H.Y.D. Scott, architects. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

a wide opportunity for the random distribution of absorbent elements and surface irregularities. The freer relationship between audience area and platform offers a wider scope in design and an increased fulfilment of several musical-acoustical requirements. It appears that, from an acoustical point of view, this floor shape offers hitherto unexplored advantages.

Figure H.5 illustrates the Philharmonie, Berlin, a recent example of an irregularly shaped Concert Hall (H-80, H-116, H-119).

(F) Combination of the foregoing shapes. This will permit the blending of the acoustical advantages of various floor shapes into a single design, thus eliminating defect-producing elements.

The Philharmonic Hall, New York, shown in Figure H.6, constitutes a mixture of several floor shapes (H-6, H-78, H-79, H-81, H-108, H-117, H-118). Other examples are:Kulttuuritalo, Helsinki (H-6); Konserttisali, Turku (H-71, H-90); Beethovenhalle, Bonn, illustrated in Figure H.10 (H-65, H-69, H-92); and Konserthus, Gothenburg (H-28, H-73, H-105).

In order to achieve the required acoustical conditions in Auditoria for music, in addition to the recommendations outlined in Section F and subsection H.1, attention should be given to following points (H-2, H-5, H-6, H-109, H-115, GB-52):

(A) Unless an Auditorium is designed specifically for a single musical program (e.g.,for large orchestral performances only), the R.T. always has to be a meticulously established compromise. A carefully controlled R.T. will (a) increase the fullness of tone, (b) promote diffusion, (c) contribute to blend, and (d) increase the dynamic range. The pure fact that a hall has an ideal R.T. at

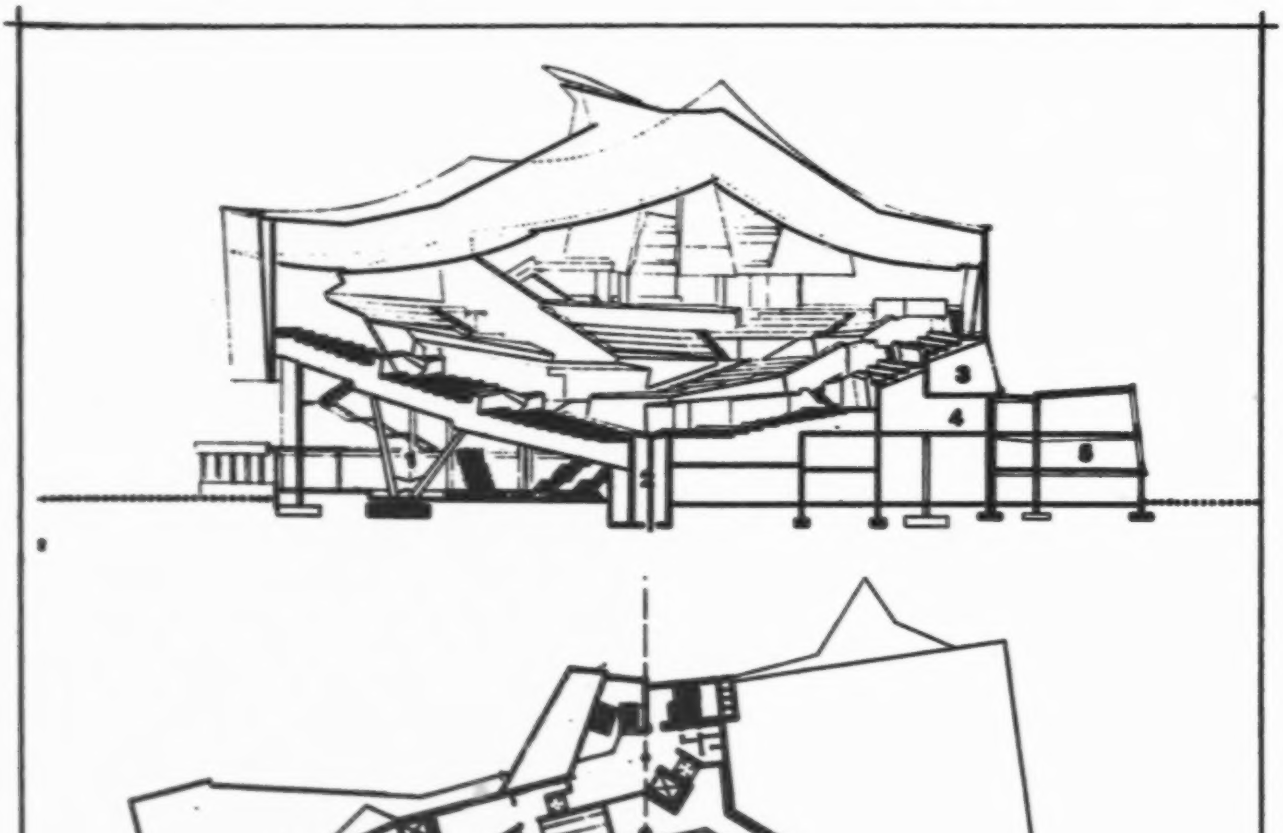


Figure H.5. Irregularly shaped Concert Hall, the "Philharmonie", Berlin. Seating capacity 2200, dedicated in 1963. Floor plan, 1: orchestra platform, 2: choir, 3: organ, 4: music gallery, 5: control room, 6: skylight; Section, 1: vestibule, 2: movable podium, 3: foyer, 4: music rooms, 5: offices. H. Scharoun, architect; L. Cremer, acoustical consultant. (Reprinted from Bauen und Wohnen, Dec. 1963).

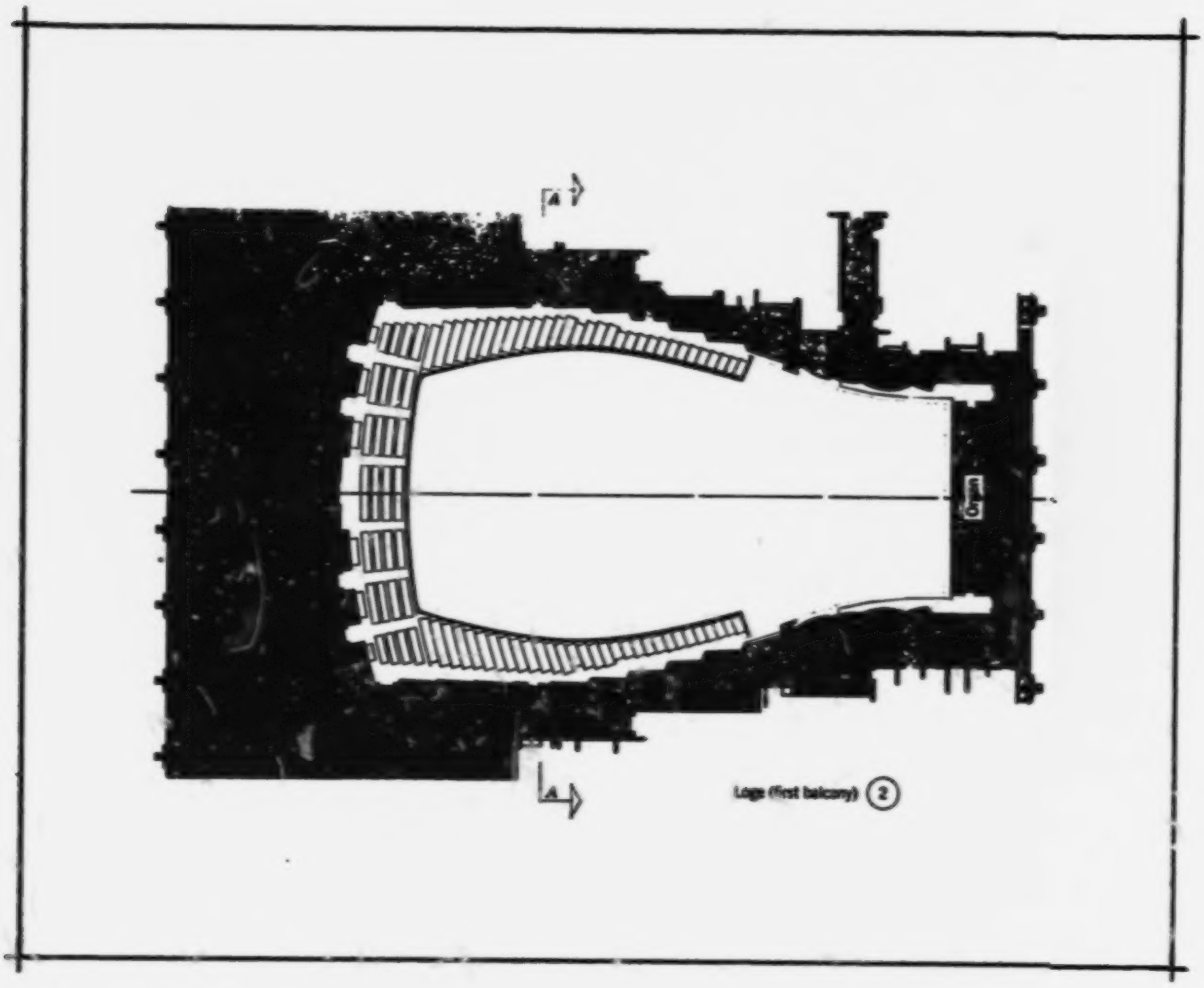


Figure H.6. Philharmonic Hall, New York, a combination of rectangular and fan-shaped halls. Plan of first balcony. M. Abramovitz, architect; Bolt, Beranek and Newman, acoustical consultants. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

the mid-frequency, will not make this room acoustically excellent for the performance of music. An otherwise too reverberant space can be rendered acoustically tolerable if the "sending end" of the room is so designed that it supplies a considerable amount of direct sounds or short-delayed first reflections to the entire audience area.

(B) The provision for an adequate supply and distribution of bass tones over the audience area is a serious acoustical problem (recently experienced in Philharmonic Hall, New York). This is due to several facts, e.g., fundamentals of a double bass are very weak, and most of the time only their harmonics are heard. It requires more effort by the performers to produce low frequency sounds than to create middle or high frequency sounds, i.e., low frequency sounds must be more powerful than middle or high frequencies in order to be heard equally well by auditors.

(C) The provision for ample short-delayed reflections is essential, but this factor by itself will not produce good hearing conditions in Auditoria for music.

(D) Definition will be satisfactory (a) if the initial-time-delay gap (paragraph H.1.A) does not exceed 20 milliseconds, (b) if the direct sound is loud enough relative to the reverberant sound (i.e., listeners are reasonably close to the sound source), and (c) if there is no echo in the hall.

(E) Brilliance will be achieved (a) if the R.T. at 500 cps and at higher frequencies is ideal related to the type of music, to the volume and purpose of the Auditorium, (b) if the direct sound is adequately loud, and (c) if a high degree of acoustical intimacy is present.

(F) Brilliance and blend will be accomplished if the enclosures around the sound source thoroughly blend and mix the sounds of various instruments so that chords are perceived as harmonious by the listeners.

(G) Immediacy of response will prevail (a) if sounds are progressively reflected back from the audience area to the sound source with graduated delays, (b) if the initial-time-delay gap is markedly short in the room, (c) if R.T. is properly controlled, (d) if a high degree of diffusion prevails, and (e) if echoes and long-delayed reflections have been eliminated from the room.

(H) Echo will be particularly noticeable if the R.T. is short and diffusion is inadequate. The longer the R.T. in a room, the less trouble is likely to be expected from echo; the longer R.T. will "cover up" the single intrusions of an echo. In checking echo-producing spots, it should be always borne in mind that the acoustical design of rooms is a three-dimensional problem.

Flutter echo can be prevented (a) if at least one of the parallel surfaces is treated with a finish that is especially efficient at the medium and high frequencies, and (b) if parallelism between opposite surfaces is avoided.

(I) To achieve uniform quality of sound over the entire seating area, (a) balconies should not protrude too deeply into the air space of the room (Figure H.7), (b) listeners should have unobstructed sight lines so that they receive ample direct sound, (c) the room should be of a reasonable size and proportion, and (d) curved (concave) enclosures should be avoided.

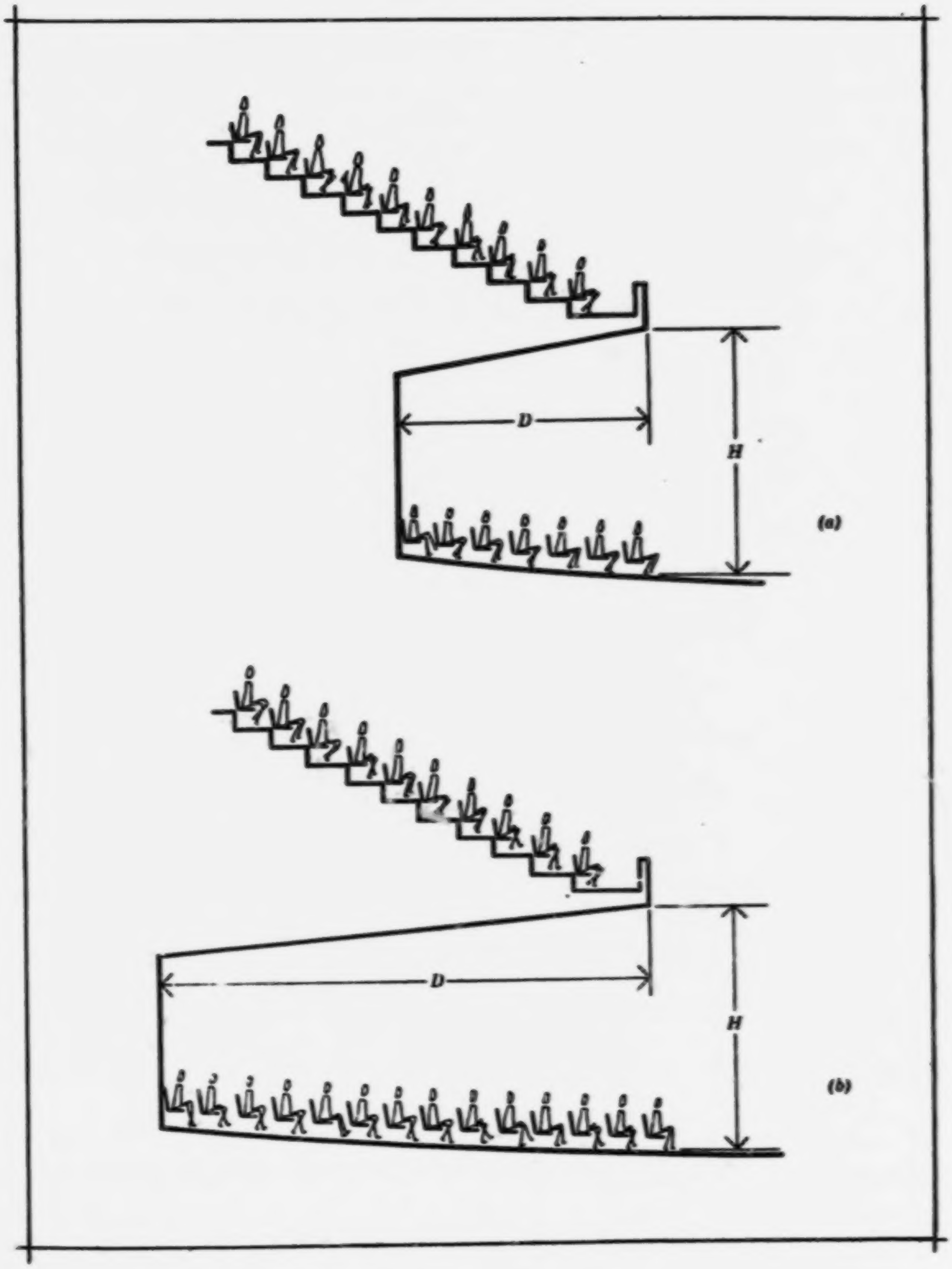


Figure H.7. Diagrammatic layouts of balconies recommended for Auditoria for music;

(a) in a Concert Hall D should not exceed H;

(b) in Opera Houses D should not exceed 2H.

(Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

H.4 Auditoria for music

H.4.1 Concert Halls

There is no specific room shape that can be considered as being ideal for a Concert Hall. At the present state of affairs, the irregular shape seems to be the most promising, as expressed in paragraph H.3.E. However, the successful integration of the various requirements will certainly necessitate the closest co-operation between architect, technical consultants and musical experts (H-21, H-29, H-31, H-32, H-36, H-37, H-58, H-59).

During the design of the platform, the following items should be checked (H-6, H-21, H-23, H-24):

- required floor area, based on space requirements of musicians, their instruments, conductor and soloists;
- expected dimensions, width to depth relation, raking, etc., to secure balance, blend and ensemble (Figure H.8);
- need for an occasional orchestra shell with variable size and volume;
- stage height relative to floor of Auditorium;
- relationship to surrounding boundary surfaces in order to provide intimacy, definition and diffusion;
- integration of mechanical, electrical and acoustical requirements;
- space and acoustical requirement for organ installation;
- surface treatment of enclosures around platform, partly to reduce unnecessary absorption and partly to enhance projection of sound;
- construction of the platform to enhance bass radiation and also to reduce overpowering sounds of the percussions;
- spatial relationship to instrument store for quick and unhampered delivery of the instruments to and from the platform.

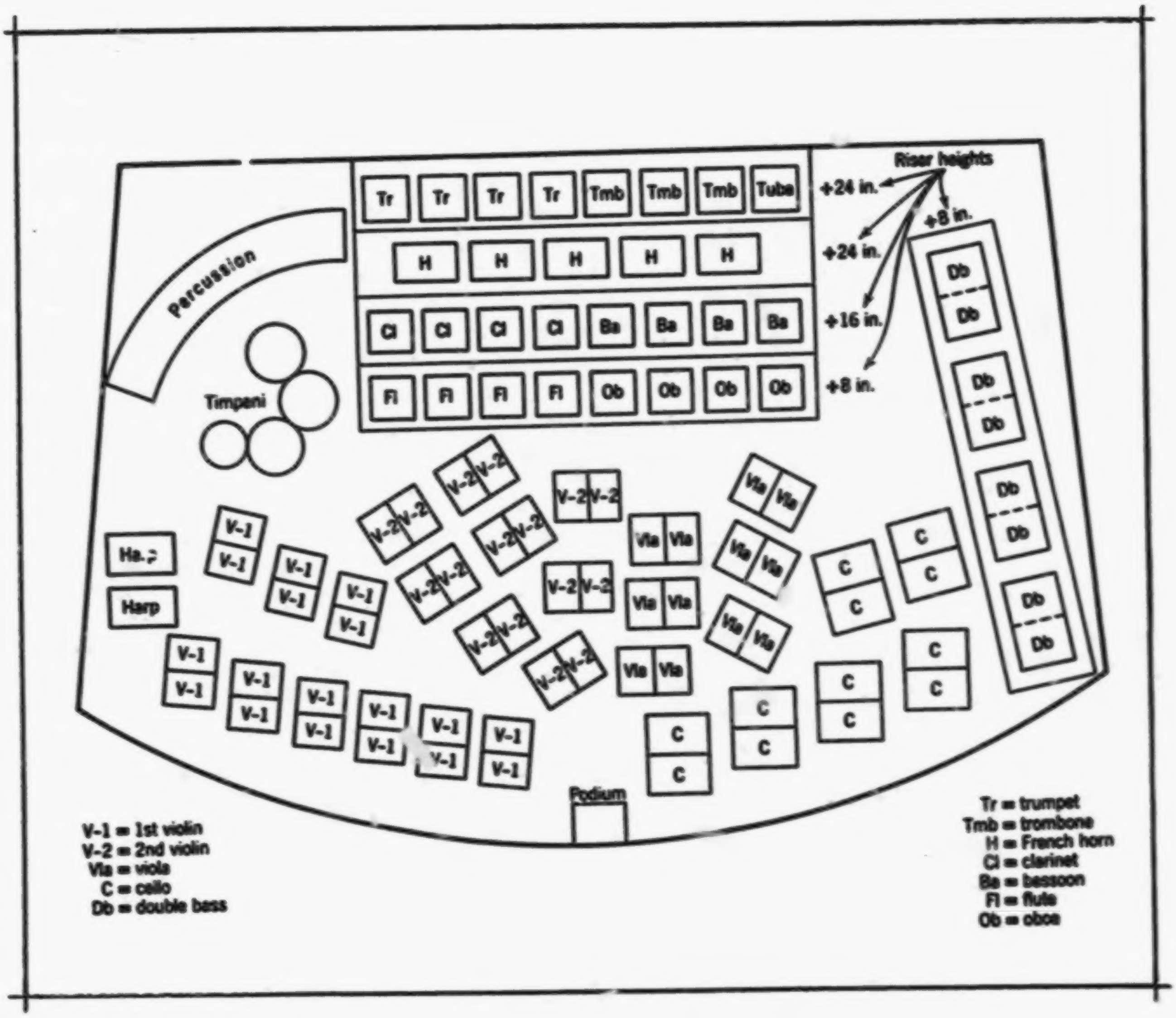

Riser heights
+24 in.
+24 in.
+16 in.
+8 in.
+8 in.
Tr
Tmb
Tuba
H
Cl
Ba
Fl
Ob
Percussion
Timpani
Harp
Harp
V-1
V-2
Vla
C
Db
Podium
V-1 = 1st violin
V-2 = 2nd violin
Vla = viola
C = cello
Db = double bass
Tr = trumpet
Tmb = trombone
H = French horn
Cl = clarinet
Ba = bassoon
Fl = flute
Ob = oboe

Figure H.8. Layout of an orchestra platform with riser heights and positions indicated for the instruments of a symphonic orchestra. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

The use of a balcony (or balconies) in large Concert Halls is advantageous because (a) it brings the audience closer to the platform, (b) it is relatively easy to supply short-delayed reflections to the steeply raked seats of the balconies, and (c) sound waves do not reach the rows of the gallery at grazing incidence as they do on the main seating area. To provide satisfactory hearing conditions under a balcony, attention is called to recommendations illustrated in Figure H.7.

Recommended volume per seat values for Concert Halls (H-76, H-109, GB-52) are:

minimum	230 ft^3
optimum	250 to 300 ft^3
maximum	350 ft^3.

Figures H.9 and H.10 illustrate two German Concert Halls built after World War II.

Table H.1 lists important architectural-acoustical data of outstanding Concert Halls (H-6).

Table H.1. Architectural-acoustical data of outstanding Concert Halls (H-6, H-109).

Name year of dedication	volume ft^3	aud. capacity	V per aud. seat	mid-fr. R.T.(full) sec
Symphony Hall, Boston; 1900 (H-83)	662,000	2631	252	1.8
Tanglewood Music Shed, Lenox, Mass.; 1938 (H-74, H-85)	1,500,000	6000	250	2.05
Carnegie Hall, New York; 1891 (H-86)	857,000	2760	311	1.7
Philharmonic Hall, New York; 1962 (H-78, H-79, H-81, H-108, H-116, H-117, H-118)	865,000	2644	327	2.0

Table H.1. Architectural-acoustical data of outstanding Concert Halls (H-6, H-109)-cont'd.

Name year of dedication	volume ft^3	aud capacity	V per aud. seat	mid-fr. R.T.(full) sec
St. Andrew's Hall, Glasgow; 1877 (H-33, H-48, H-98)	569,000	2133	267	1.9
Royal Festival Hall, London; 1951 (H-20, H-34, H-39, H-42, H-49, H-50, H-101)	775,000	3000	258	1.47
Beethovenhalle, Bonn; 1959 (H-69, H-92)	555,000	1407	395	1.7
Liederhalle, Grosser Saal, Stuttgart; 1956 (H-57, H-63, H-95, H-112)	565,000	2000	283	1.62
Philharmonie, Berlin; 1963 (H-80, H-116, H-119)	920,000 ●	2200	355 ●	2.0
Grosser Musikvereinssaal, Vienna; 1870 (H-88, H-110)	530,000	1680	315	2.05
Neues Festspielhaus, Salzburg; 1960 (H-87, H-114)	547,500	2158	254	1.5
Konserttisali, Turku; 1953 (H-71, H-90)	340,000	1002	339	1.6
F.R. Mann Concert Hall, Tel Aviv; 1957 (H-62, H-103)	750,000	2715	276	1.55
Concertgebouw, Amsterdam; 1887 (H-104)	663,000	2206	301	2.0
Konserthus, Gothenburg; 1935 (H-28, H-73, H-105)	420,000	1371	306	1.7
Stadt-Casino, Basel; 1876 (H-106)	370,000	1400	264	1.7

● estimated figures

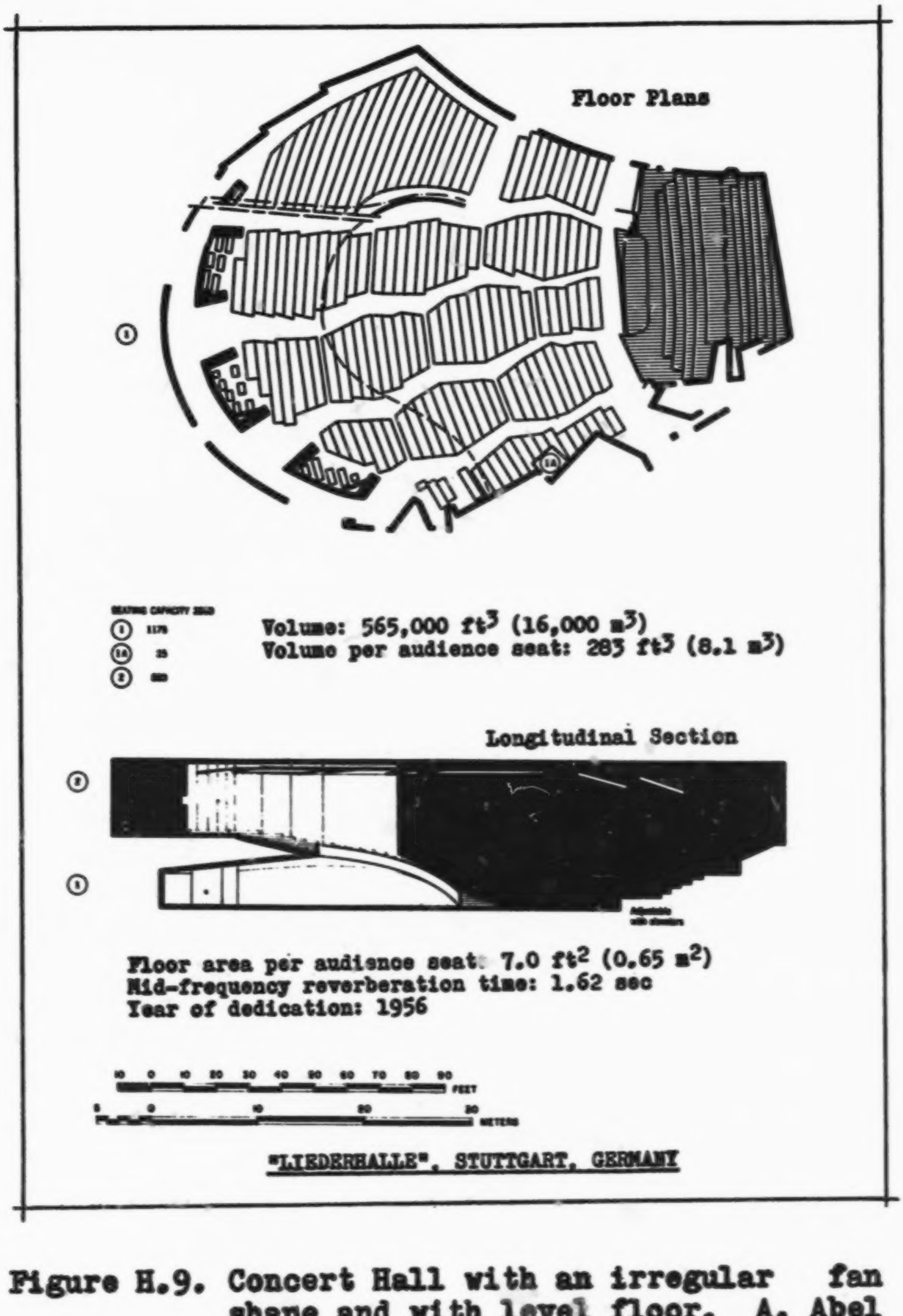
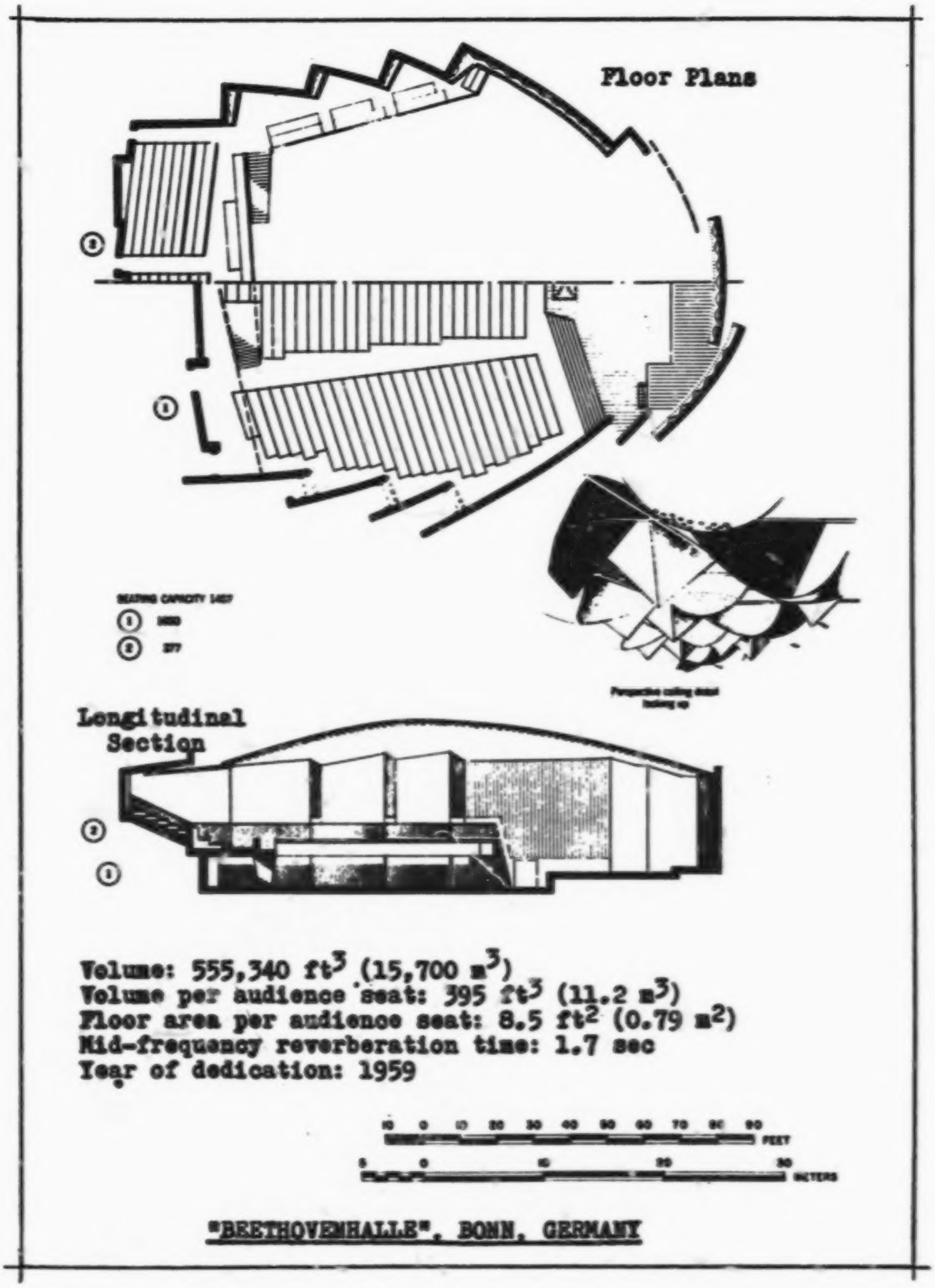

Floor Plans
SEATING CAPACITY
1 1175
1A 25
2
1A
1
Volume: 565,000 ft³ (16,000 m³)
Volume per audience seat: 283 ft³ (8.1 m³)
Longitudinal Section
2
1
Floor area per audience seat: 7.0 ft² (0.65 m²)
Mid-frequency reverberation time: 1.62 sec
Year of dedication: 1956
10 0 10 20 30 40 50 60 70 80 90 FEET
5 0 10 20 30 METERS
"LIEDERHALLE", STUTTGART, GERMANY

Figure H.9. Concert Hall with an irregular fan shape and with level floor. A. Abel and R. Gutbrod, architects; L. Cremer, acoustical consultant. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).



Floor Plans
①
②
SEATING CAPACITY 1407
① 1030
② 377
Longitudinal Section
FEET
METERS
"BEETHOVENHALLE", BONN, GERMANY

Volume: 555,340 ft^3 (15,700 m^3)
Volume per audience seat: 395 ft^3 (11.2 m^3)
Floor area per audience seat: 8.5 ft^2 (0.79 m^2)
Mid-frequency reverberation time: 1.7 sec
Year of dedication: 1959

Figure H.10. Concert Hall with an irregular layout and with level floor. S. Wolske, architect; E. Meyer, acoustical consultant. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

H.4.2 Opera Houses

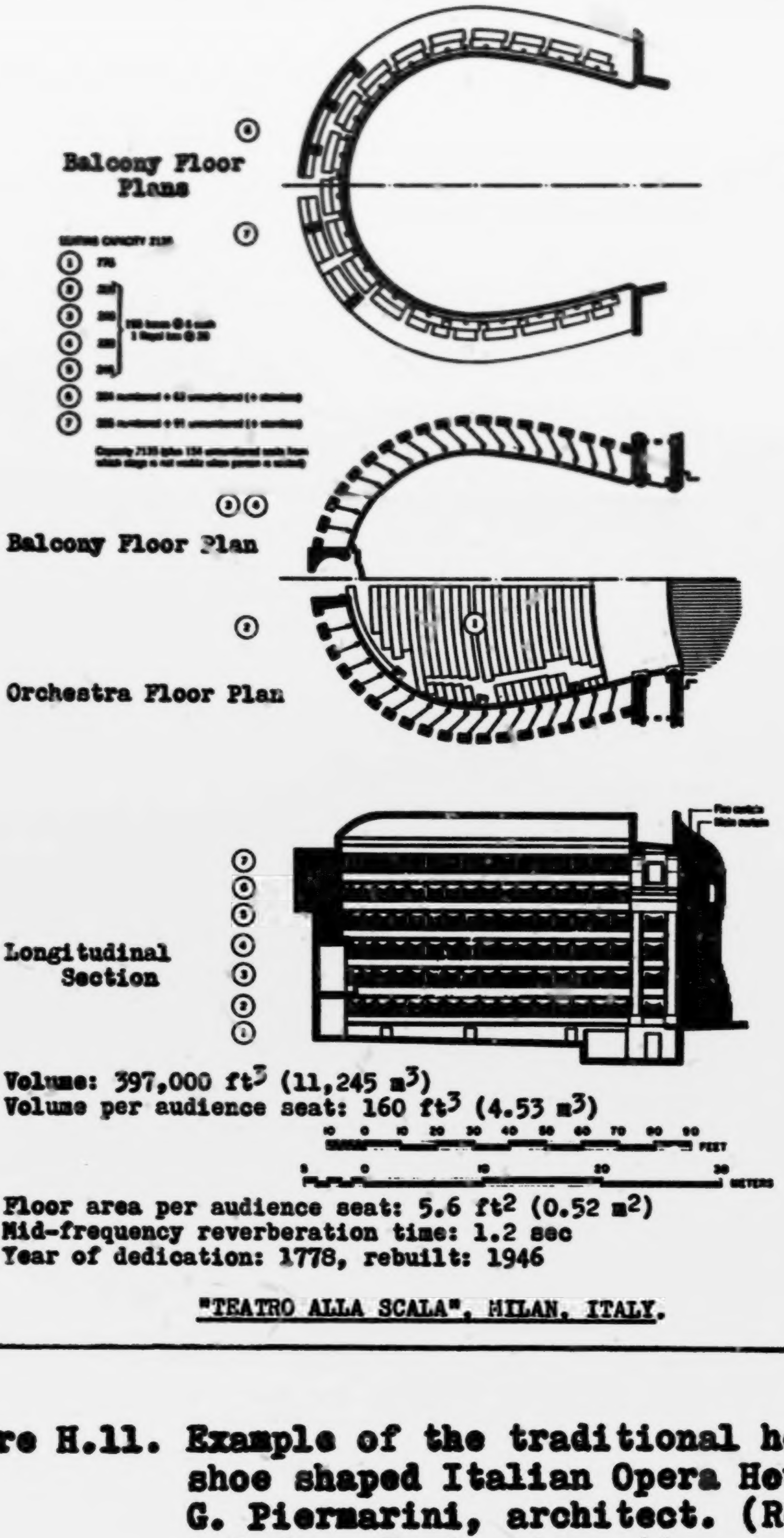
Strictly speaking,an Opera House is the combination of a Legitimate Theater and a Concert Hall, consequently the pertinent recommendations discussed in paragraphs G.4.1 and H.4.1 should be followed (H-21).

The traditional horseshoe shaped, Italian-type Opera House with its highly absorbent rings of boxes and with its relatively short R.T. (about 1.2 sec) still suggests the best architectural layout for Mozartian (or European) Operas, illustrated in Figure H.11. The State Opera of Hamburg, Germany, is a contemporary version of the same type with straightened walls, illustrated in Figure H.12 (H-125, H-142).

The Festival Opera House at Bayreuth, Germany, was constructed to satisfy Wagner's musical style exclusively (Figure H.13). The tiers of balconies were eliminated in this Auditorium,creating a R.T. of 1.55 sec (with capacity audience), with high fullness of tone and reduced definition, unsuitable for European operas (H-120, H-135, H-140).

During the design of the orchestra pit, the following items should be checked:

- required floor area based on space requirements of musicians and conductor;
- expected dimensions, width to depth relation in order to secure balance within orchestra;
- relationship of pit floor level to stage floor and audience area to provide singer-orchestra balance and also to suit required dynamic range;
- construction of floor and walls to achieve adequate projection of sound into audience area;
- adjustability of pit volume to suit orchestras of different sizes.


Balcony Floor Plans
Balcony Floor Plan
Orchestra Floor Plan
Longitudinal Section
FEET
METERS

Volume: 397,000 ft^3 (11,245 m^3)
Volume per audience seat: 160 ft^3 (4.53 m^3)

Floor area per audience seat: 5.6 ft^2 (0.52 m^2)
Mid-frequency reverberation time: 1.2 sec
Year of dedication: 1778, rebuilt: 1946

"TEATRO ALLA SCALA", MILAN, ITALY.

Figure H.11. Example of the traditional horseshoe shaped Italian Opera House. G. Piermarini, architect. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

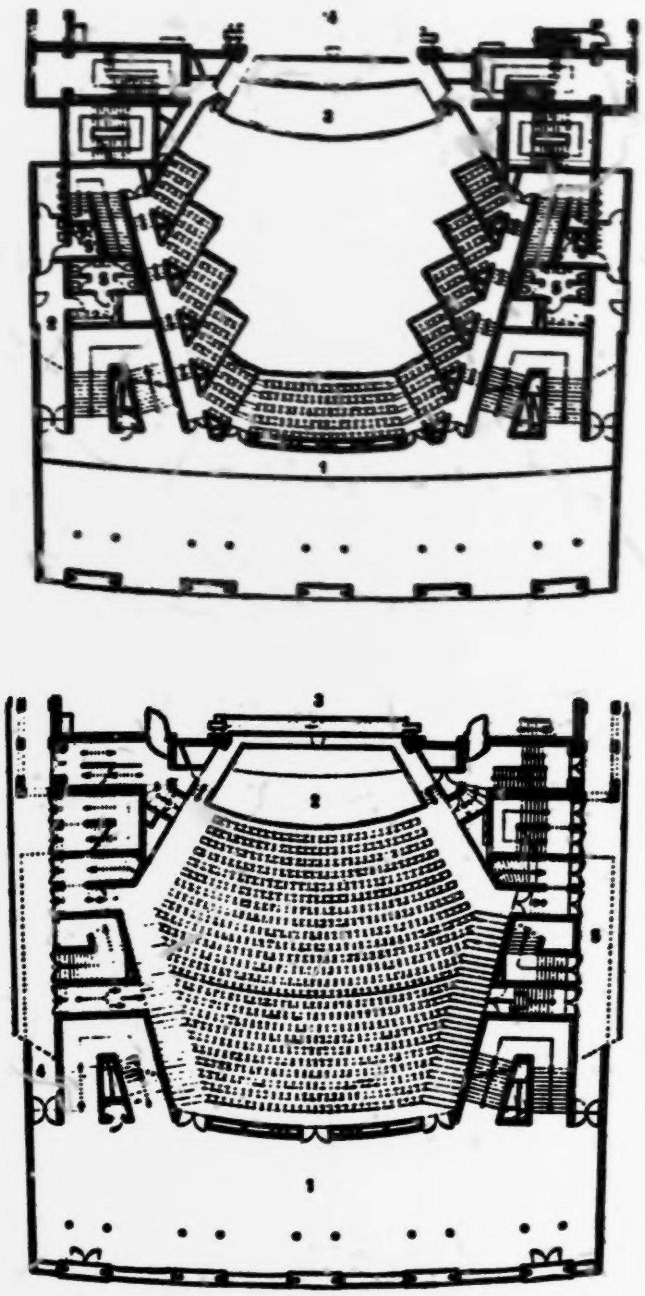


Figure H.12. State Opera House, Hamburg, Germany, a contemporary version of the Italian Opera House. Main floor (bottom), 1: main vestibule, 2: orchestra pit, 3: stage ; Plan at first balcony level (above), 1: balcony corridor, 3: space above main floor, 4: stage tower. G. Weber, architect; D. Eisenberg, acoustical consultant. (Reprinted from Architetture Per Lo Spettacolo by R. Aloi, Ulrico Hoepli, Milano, 1958).

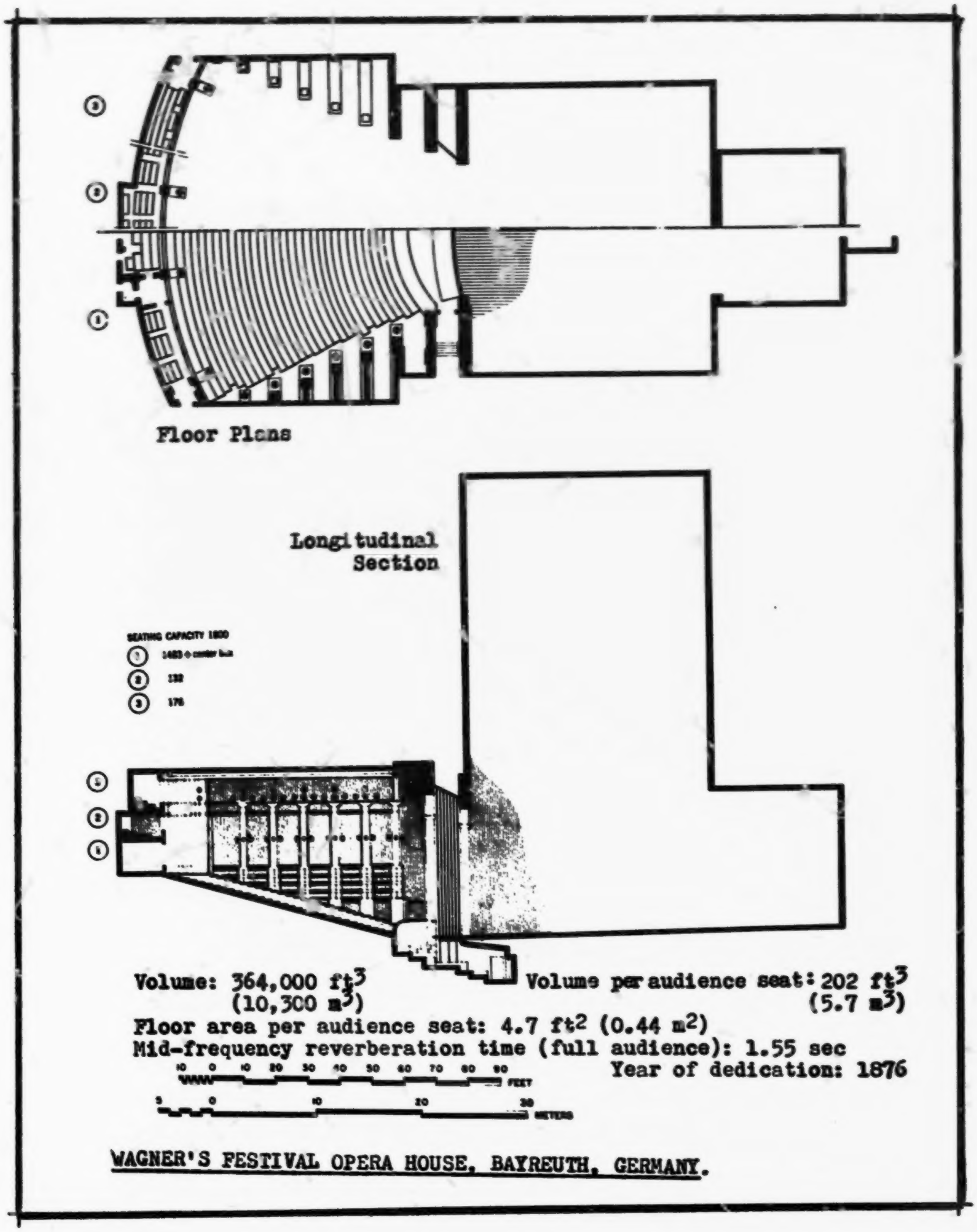

Floor Plans
Longitudinal Section
SEATING CAPACITY 1800
① 1492 + center box
② 132
③ 176
Volume: 364,000 ft^3 (10,300 m^3)
Volume per audience seat: 202 ft^3 (5.7 m^3)
Floor area per audience seat: 4.7 ft^2 (0.44 m^2)
Mid-frequency reverberation time (full audience): 1.55 sec
Year of dedication: 1876
10 0 10 20 30 40 50 60 70 80 90 FEET
5 0 10 20 30 METERS
WAGNER'S FESTIVAL OPERA HOUSE, BAYREUTH, GERMANY.

Figure H.13. An Opera House built to suit Richard Wagner's personal musical style. O. Brückwald, architect. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

In the relationship between audience area and stage tower, "coupled spaces" should be eliminated. The stage tower, however, should not be rendered too "dead" so that the singers will not be deprived of the helpful reverberant environment.

The provision for an apron stage, protruding into the audience area, is recommended. This will reduce the average distance between singers and audience, and will render the ceiling reflectors more effective in the supply of short-delayed reflections to the audience (GB-53).

Recommended volume per seat values for Italian-type Opera Houses (H-5, H-6, H-109, GB-52) are:

minimum	140 ft^3
optimum	150 to 180 ft^3
maximum	200 ft^3.

Table H.2 lists important architectural-acoustical data of outstanding Opera Houses (H-6, GB-52).

Table H.2. Architectural-acoustical data of outstanding Opera Houses (H-6, GB-52).

Name year of dedication	volume ft^3	aud. capacity	V per aud. seat	mid-fr. R.T.(full) sec
Academy of Music, Philadelphia; 1857 (H-6)	533,000	2836	188	1.35
Metropolitan Opera House, New York; 1883 (H-129)	690,000	3639	183	1.2
Royal Opera House, London; 1858 (H-136)	432,500	2180	196	1.1
Festspielhaus, Bayreuth; 1876 (H-135, H-140)	364,000	1800	202	1.55
Teatro Colon, Buenos Aires; 1908 (H-132)	726,300	2487	261	1.7

Table H.2. Architectural-acoustical data of outstanding Opera Houses (H-6, GB-52)-cont'd.

Name year of dedication	volume ft^3	aud. capacity	V per aud. seat	mid-fr. R.T.(full) sec
Staatsoper, Vienna; 1869 (H-133, H-141)	376,600	1658	195	1.3
Théatre National de l'Opéra, Paris; 1875 (H-134)	352,000	2131	158	1.1
Teatro alla Scala, Milan; 1778 (H-121, H-137)	397,000	2289	160	1.2
Staatsoper, Hamburg; 1955 (H-125, H-142)	340,000	1650	207	1.25
Staatsoper, Cologne; 1957	305,000	1346	225	1.5

H.4.3 Music Rooms, Rehearsal Rooms

The acoustical requirements reviewed in Section F, subsections G.3 and H.3,naturally apply, bearing in mind that the achievement of the relevant musical acoustical attributes in these relatively small rooms will be a lot easier than in Concert Halls or Opera Houses. Suitably shaped room enclosures, adequately controlled R.T., properly chosen and well distributed acoustical finishes, and the required degree of noise control (in both directions !) will produce acoustically efficient Music Rooms and Rehearsal Rooms (H-144, H-145, H-147, H-148, H-149, H-150, H-151).

If excellent acoustical conditions are expected, the R.T. should be adjustable to satisfy specific requirements of the prevailing sound program (H-145, GB-21).

Acoustical conditions in Rehearsal Halls should simulate those of the Auditorium proper with which they are functionally connected (GB-43).

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relative to Section H: "Acoustical Design of Rooms for Music"

(See list of abbreviations on page 1)

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Section I. Places of Assembly with Special Acoustical Requirements

I.1 Churches
I.2 Multi-Purpose Auditoria, Community Halls
I.3 Motion Picture Theaters
I.4 Open-Air Concert Platforms, Open-Air Theaters, Drive-In Theaters
References

The Auditoria discussed in preceding Sections are used, without exception, for multiple purposes, nevertheless, in their acoustical design priority has to be given either to speech (Section G) or to music (Section H).

This Section will deal with Places of Assembly in which more or less equally favorable acoustical conditions must be secured for both speech and music (I-1, I-14, I-17).

I.1 Churches

Excessive reverberation and absence of speech intelligibility are the main acoustical features (rather defects) of medieval Churches, particularly of the larger ones (I-15). These acoustical characteristics have not only influenced the style of organ music composed for the Church, but have left their mark on the liturgical pattern as well; furthermore, the adoption of polyphonic choral music, the chanting of spoken words and even perhaps the use of an archaic tongue must have been associated with the highly reverberant conditions prevailing in medieval Church Auditoria (I-1, I-2, I-3, I-4, I-18, I-39).

The recent revolution in Church architecture seems to attach growing importance to improved environmental conditions within Churches.

Church Auditoria usually consist of several coupled spaces (nave, chancel, chapel, baptistry, confessionals, organ, choir loft, etc.). In their acoustical design, therefore, consideration must be given to the acoustical requirements of these individual spaces (I-1), as follows:

(a) the chancel area and the pulpit should be well elevated and surrounded by reflective enclosures to provide favorable conditions for the projection of speech sound toward the congregation (Figure I.1);

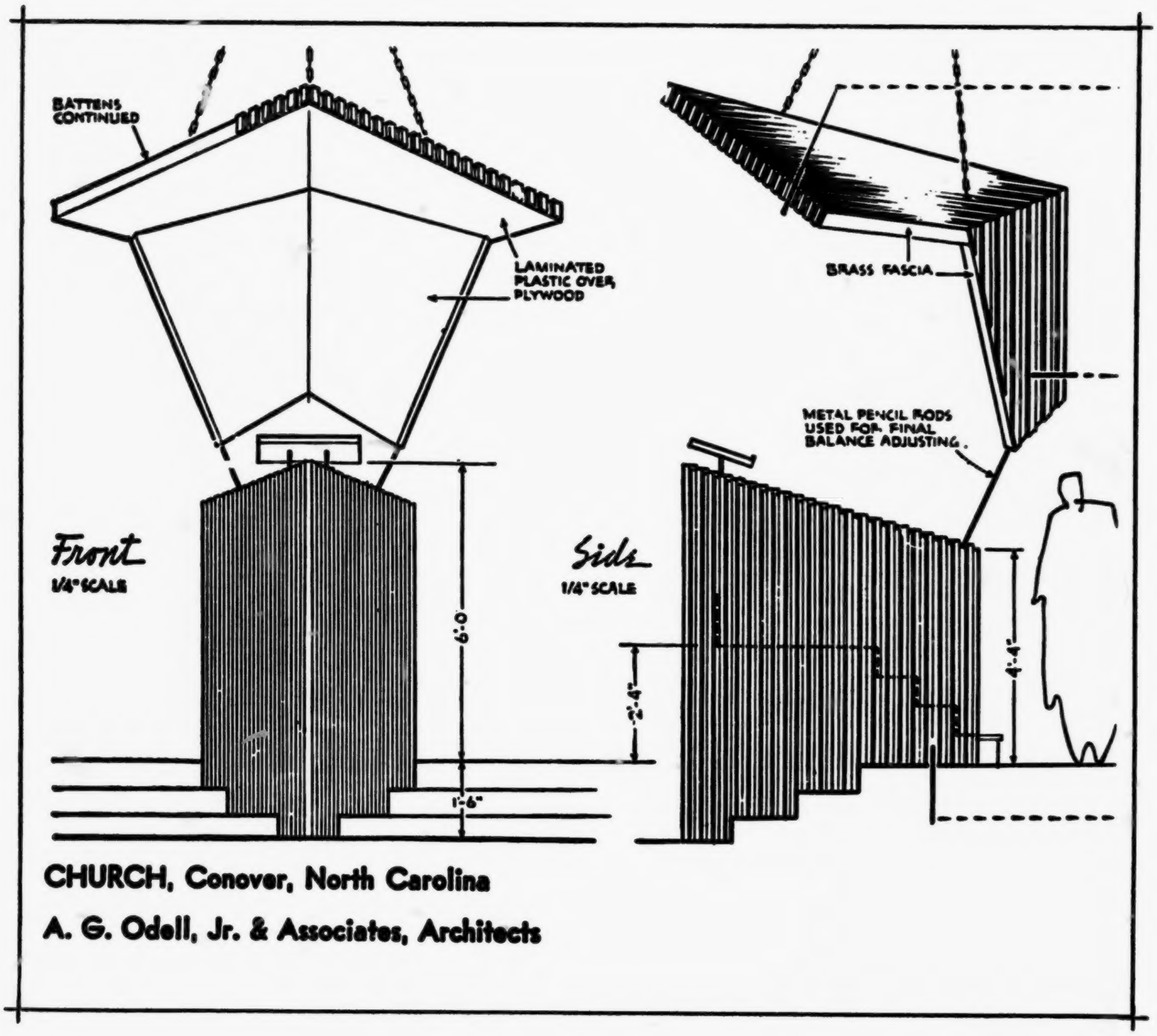

BATTENS CONTINUED
LAMINATED PLASTIC OVER PLYWOOD
BRASS FASCIA
METAL PENCIL RODS USED FOR FINAL BALANCE ADJUSTING.
Front
1/4" SCALE
Side
1/4" SCALE
6'-0"
1'-6"
2'-4"
4'-4"
CHURCH, Conover, North Carolina
A. G. Odell, Jr. & Associates, Architects

Figure I.1. Sound reflector integrated into the design of a pulpit. (Reprinted from Progr. Arch., Dec. 1959).

(b) the organ and choir should be located in an area that provides a favorable acoustical environment for the generation of music; they should be surrounded by reflective surfaces without creating echoes, flutter echoes or sound concentrations. The spatial relationship between organist, organ, choir-master and choir must be carefully considered (I-11, I-13, I-16, I-18, I-19, I-22, I-23, I-27, I-34);

(c) every sector of the congregation should enjoy good listening conditions for every part of the religious service. Since the room volume is always more than necessary in a Church Auditorium, the control of R.T. will definitely require the use of a certain amount of acoustical finishes;

(d) coupled spaces require individual reverberation control so that reverberation conditions in these spaces will not conflict with those prevailing in the main body of the Church Auditorium;

(e) extraordinary care should be exercised in the elimination of noises, a prerequisite to peaceful meditation and prayer.

Acoustical problems become more complicated and more involved as the volume of the Church Auditorium increases (I-16, I-28, I-39), particularly if the floor shape is circular or curved (I-38, I-45). Circular floor shapes generally are dome roofed, thereby creating serious acoustical defects (echoes, sound concentrations, long-delayed reflections, uneven distribution of sound, etc.). These defects can be eliminated by the application of highly absorptive finishes over the critical surfaces or by shielding the curved enclosures from directly incident sound by large suspended reflectors or diffusers (I-24, I-29).

Figure I.2 illustrates the floor plan of the well known cylindrical MIT Chapel, at Cambridge, Mass. An undulating wall inside the Chapel prevents any focusing of sound,and absorbing material behind a brick grille controls reverberation; these details are shown in Figure I.3 (I-20, I-21).

In the acoustical design of Churches it is essential to consider the nature of the religious service for different denominations because the optimum R.T. will depend on whether speech or music is regarded the more important portion of the service. Preference has to be given to the more important element since it is not feasible to provide excellent hearing conditions for both speech and music at the same time. Recommended reverberation times for Church Auditoria of various religions were shown in Figure F.3 (I-1, GB-43). Depending on the relative importance of speech or music in the particular religious service under consideration, the pertinent recommendations discussed in Sections F, G and H should be observed.

It is obvious from Figure F.3,that a wide gap exists between the optimum R.T. for speech and for organ. It will be difficult, therefore,to decide on the most acceptable compromise between these two types of sound program, particularly in Churches with special accent on the full effectiveness of an organ installation (I-11, I-16). This situation might become serious in cases when room acoustical measures to be taken are in the exclusive hands of the organ builder. In the interest of an overwhelmingly soaring organ tone, he will seldom, if ever, hesitate to recommend a R.T. that favors organ music only, disregarding the requirements of speech intelligibility. The serious consequences of such an attitude (absence of speech intelligibility, thereby inducing the congregation to lose interest in the sermon) is all too well known.

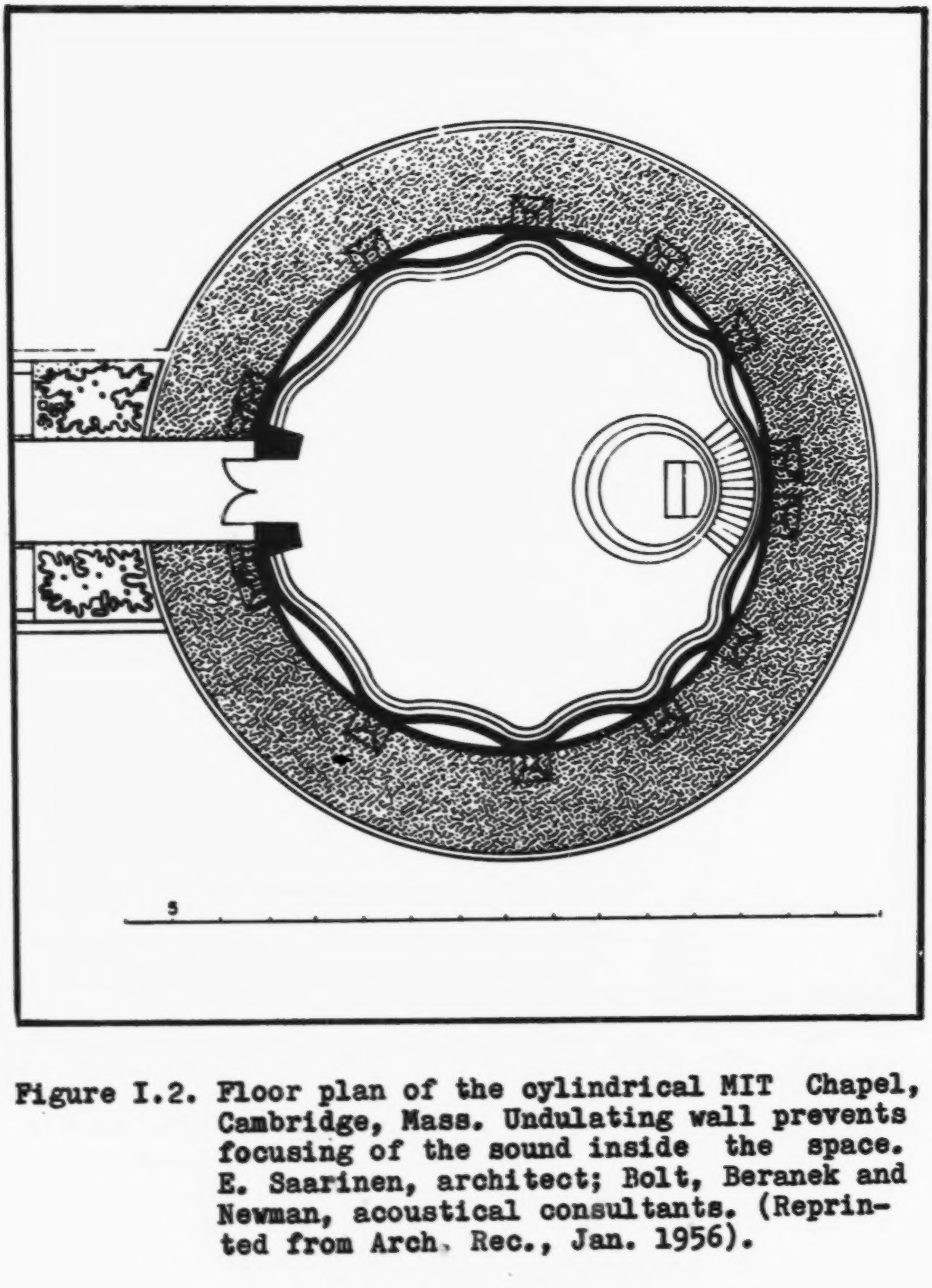


Figure I.2. Floor plan of the cylindrical MIT Chapel, Cambridge, Mass. Undulating wall prevents focusing of the sound inside the space. E. Saarinen, architect; Bolt, Beranek and Newman, acoustical consultants. (Reprinted from Arch. Rec., Jan. 1956).

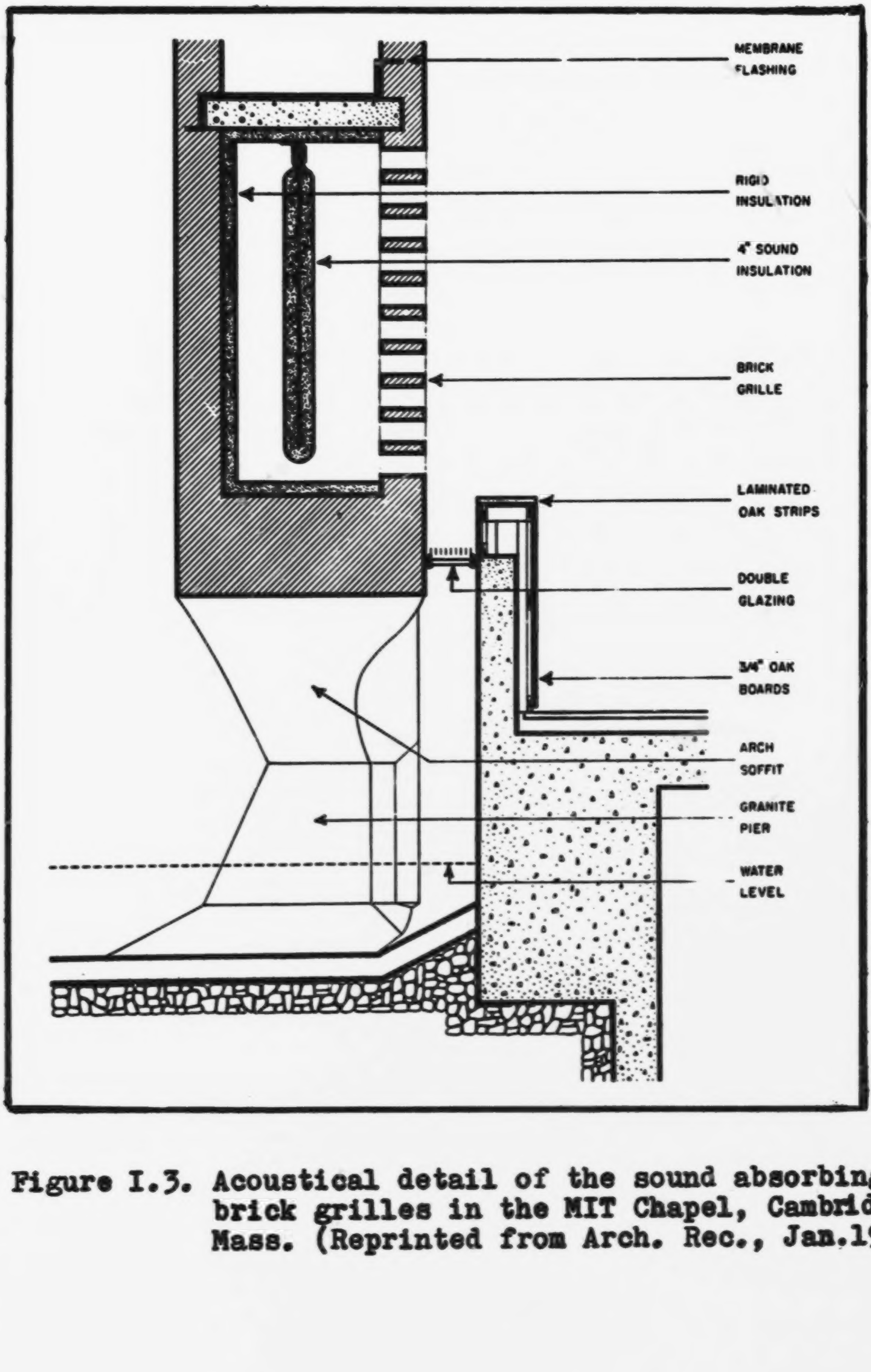

MEMBRANE FLASHING
RIGID INSULATION
4" SOUND INSULATION
BRICK GRILLE
LAMINATED OAK STRIPS
DOUBLE GLAZING
3/4" OAK BOARDS
ARCH SOFFIT
GRANITE PIER
WATER LEVEL

Figure I.3. Acoustical detail of the sound absorbing brick grilles in the MIT Chapel, Cambridge, Mass. (Reprinted from Arch. Rec., Jan.1956).

Average volume per seat values for Church Auditoria (I-1, I-16, I-23, I-39, I-42) are:

minimum 200 ft^3
optimum 250 to 350 ft^3
maximum 420 ft^3.

According to T.D. Northwood (I-39), unaided speech is possible for well-designed volumes as great as 200,000 ft^3, but the range 100,000 to 200,000 ft^3 will require careful use of reflecting surfaces to obtain maximum utilization of the available speech power. (See also Section L, pages 292-293).

Figure I.4 shows the floor plan of the elliptically shaped Notre Dame d'Anjou Church, in Ville D'Anjou, Quebec. The pulpit is located very close to one of the focal points of the ellipse. Sound concentrations have been completely eliminated and reverberation has been satisfactorily controlled by the use of pierced concrete blocks on all curved walls and by the installation of a directional sound system (I-45).

A speech amplification system should be so designed, layed out, and operated, that the congregation will be unaware of its existance. Because of the ever increasing number and intensity of noise sources inside and outside the Church buildings, the use of speech amplification systems is gradually becoming necessary even in Churches of relatively small volumes.

I.2 Multi-Purpose Auditoria, Community Halls

Since this subsection is concerned with Auditoria serving the widest range of functions, in their acoustical design the general principles given in Section F, with additional recommendations for speech and music, outlined in Sections G and H respectively, should be followed. School Auditoria and Civic (or Municipal) Auditoria are typical examples of halls falling in

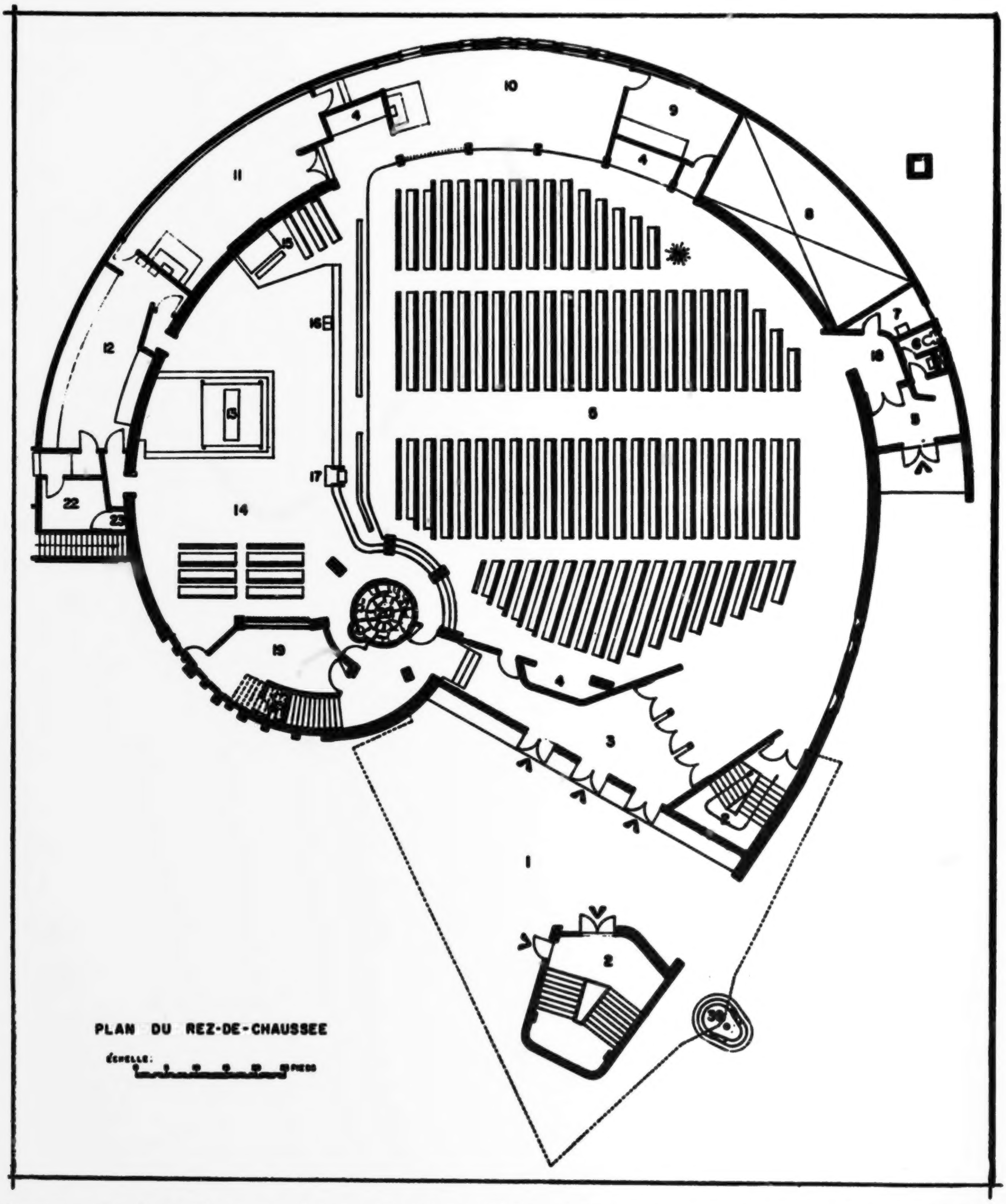

10
4
9
4
11
15
8
16
12
13
17
14
22
23
19
3
1
2
PLAN DU REZ-DE-CHAUSSEE
ÉCHELLE:

Figure I.4. Floor plan of the elliptically shaped Notre Dame d'Anjou Church, Ville d'Anjou, Quebec. Sound concentrations were eliminated and reverberation was controlled in the Church Auditorium by the use of a pierced concrete block wall all around, and by the installation of a directional speech reinforcement system. 1: entrance, 3: vestibule, 4: confessionals, 5: nave, 10 and 11: chapels, 13: altar, 14: chancel, 15: choir, 16: lectern, 17: pulpit, 19: cry room, 20: baptistry. A. Blouin, architect; L.L. Doelle, acoustical consultant.

this group. They will best serve their diverse use if the most reasonable compromise between optimum acoustical properties for speech and for music is made in their design.

A special acoustical problem is often created in Civic Auditoria by the level floor required for particular occasions; such as, conventions, exhibitions, bazaars, dances, social gatherings, etc. A level floor introduces the following acoustical problems: (a) it will be difficult to supply the audience with the required amount of direct sound (GB-53), (b) if the ceiling is reflective and horizontal, interreflections (flutter echoes) might originate between floor and ceiling when the audience area is cleared of chairs (GB-53), (c) the portable chairs usually have, if at all, a negligible amount of upholstering, thus furnishing much less absorption than do those which are fully upholstered (I-46).

In the acoustical design of these, often very large, Auditoria, (a) the "sending end" should be elevated as high as sight lines will allow (I-46, GB-53); (b) a large amount of reflective surfaces (panels) have to be located near the sound source, and, as necessary, suspended from the ceiling to provide short-delayed, reflected sound energy; these reflective surfaces have to be oriented so as to secure evenly distributed natural sound reinforcement throughout the entire Auditorium (I-46, I-47, I-49, I-68, I-70, I-75); (c) the stage should protrude as far as possible into the audience area (I-46, GB-43, GB-53); (d) an attempt should be made to accommodate a raked or raised portion of the floor at least at the sides and at the rear of the main audience area (GB-53); (e) optimum R.T. should be secured for one half of capacity audience because a considerable fluctuation has to be expected with the occupancy of these halls (I-46); (f) the loudspeaker, if used, should be located somewhat higher than it would be in an Auditorium with a ramped floor (GB-21).

For School Auditoria a sound amplification system will be necessary if the volume is in excess of the following (GB-21):

for Elementary Schools : about 40,000 ft^3
for High Schools : about 50,000 ft^3
for Colleges and Universities : about 60,000 ft^3.

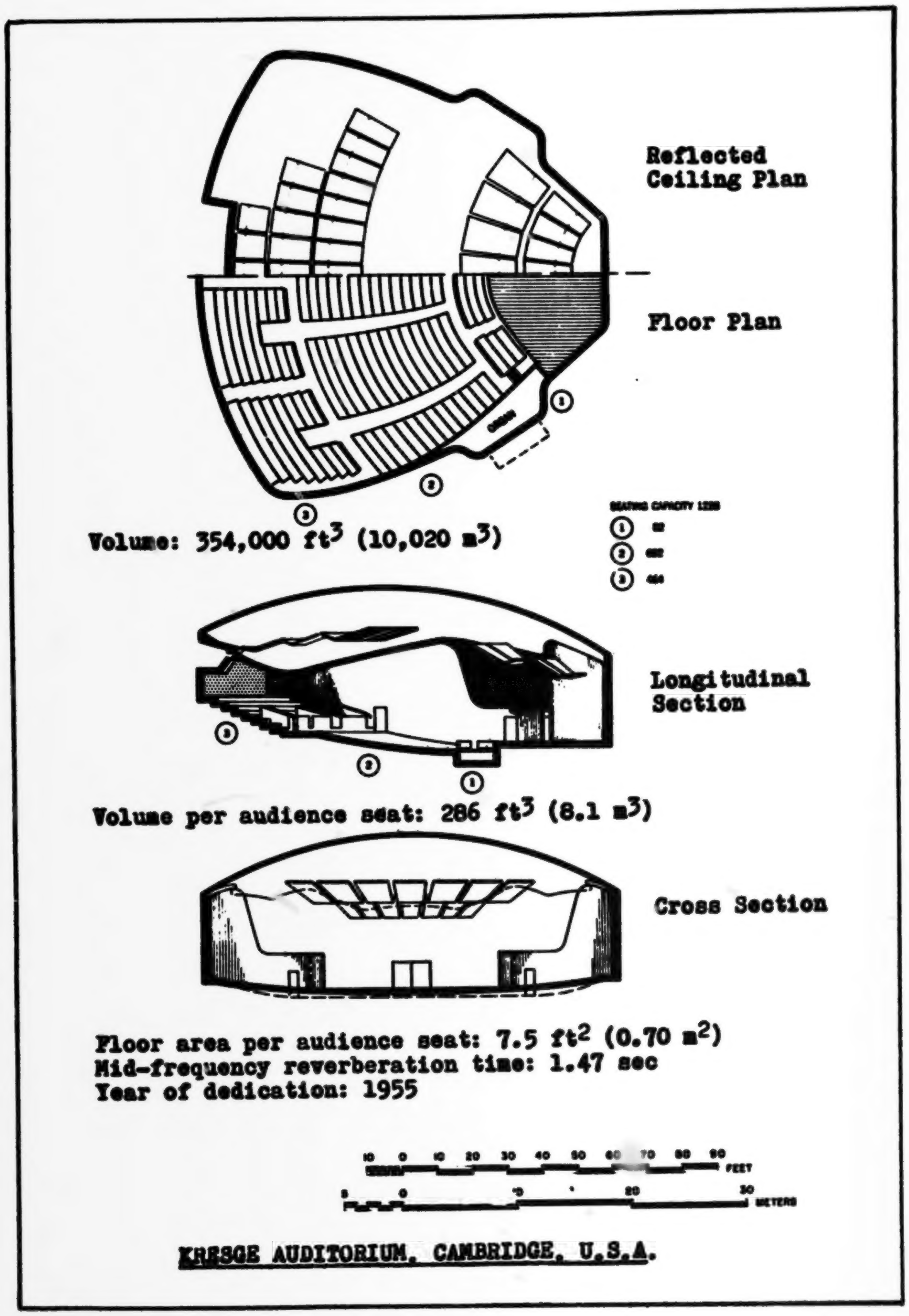
Figure I.5 illustrates the well known Kresge Auditorium in Cambridge, Mass. (I-47, I-70). Figure I.6 shows the all-purpose Jubilee Auditoria, built from the same plans, in Edmonton and Calgary, Alberta (I-51, I-53, I-71). Figure I.7 presents the Place des Arts, in Montreal (I-68). The Queen Elizabeth Theater, in Vancouver, another fine example of Multi-Purpose Auditoria, is shown in Figure G.2 (I-72).

I.3 Motion Picture Theaters

In the various types of Auditoria discussed so far both the sound source and the audience are present and both are "live"; in such Auditoria, assuming any normal sound source, hearing conditions will depend solely upon the acoustical qualities of the room.

In Motion Picture Theaters the original sound source is not present, it is only reproduced from the sound track of the film by the loudspeaker. The reproduced sound, presented in the Cinema Auditorium, will contain the acoustical characteristics of the Motion Picture Studio where the particular scene of the film was shot. It might contain, for example, the acoustical features of a Cathedral (with a R.T. of 8 sec), or of a snow field (an acoustically "dead" space), as the case may be. This means that the sound track on the film possesses a "built-in" R.T. independent of the R.T. of the Motion Picture Theater in which the audience happens to watch the movie (I-77, I-79, I-94, I-95, I-97).

It is an important goal in the acoustical design of Motion Picture Theaters that the room acoustical effect of the Cinema


Reflected Ceiling Plan
Floor Plan
①
②
③
SEATING CAPACITY
①
②
③
Longitudinal Section
Cross Section
FEET
METERS

Volume: 354,000 ft^3 (10,020 m^3)

Volume per audience seat: 286 ft^3 (8.1 m^3)

Floor area per audience seat: 7.5 ft^2 (0.70 m^2)
Mid-frequency reverberation time: 1.47 sec
Year of dedication: 1955

KRESGE AUDITORIUM, CAMBRIDGE, U.S.A.

Figure I.5. Multi-Purpose Auditorium in Cambridge, Mass. E. Saarinen, architect; Bolt, Beranek and Newman, acoustical consultants. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

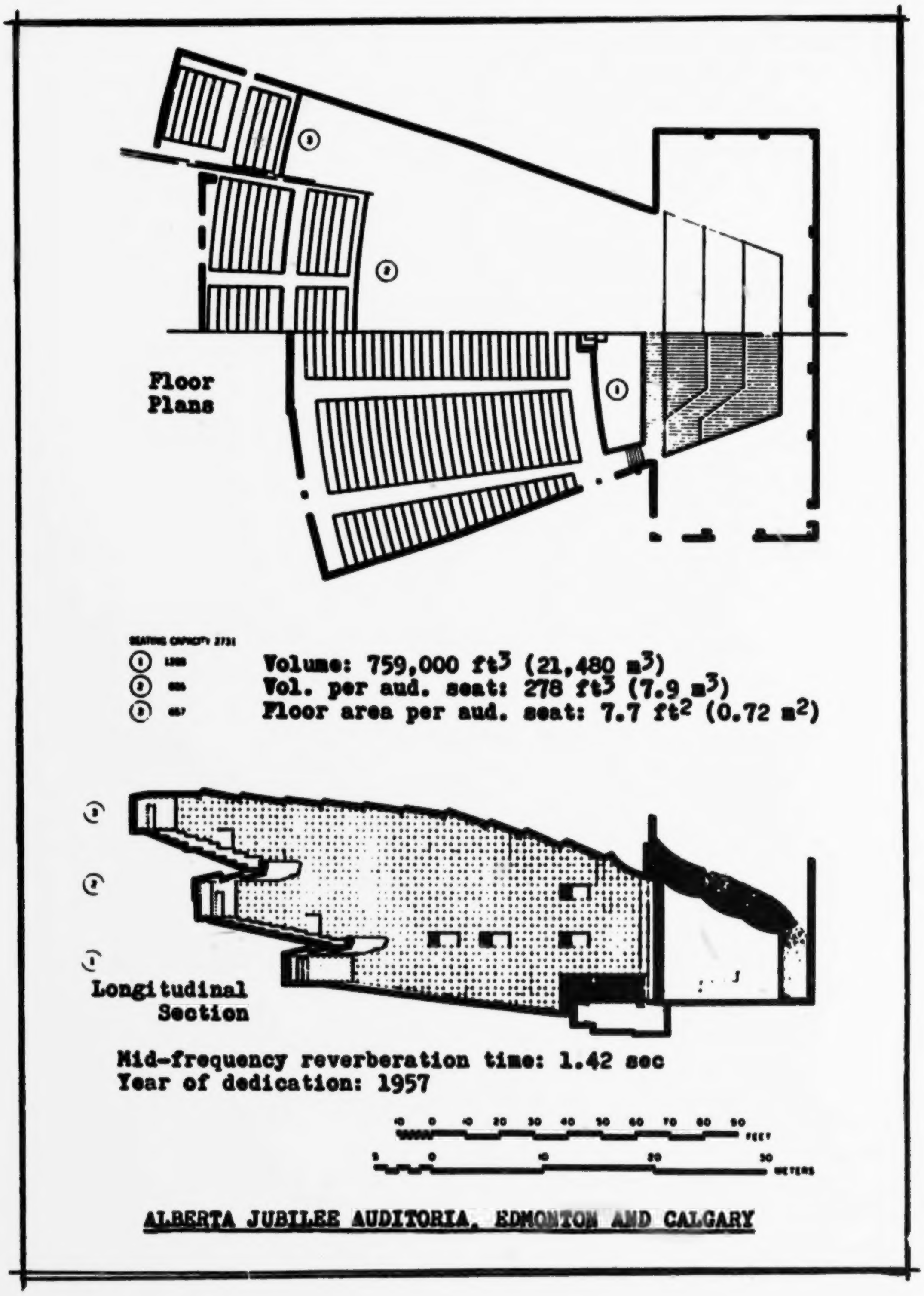

Floor Plans
SEATING CAPACITY 2731
①
②
③
Volume: 759,000 ft3 (21,480 m3)
Vol. per aud. seat: 278 ft3 (7.9 m3)
Floor area per aud. seat: 7.7 ft2 (0.72 m2)
Longitudinal Section
Mid-frequency reverberation time: 1.42 sec
Year of dedication: 1957
FEET
METERS
ALBERTA JUBILEE AUDITORIA, EDMONTON AND CALGARY

Figure I.6. Multi-Purpose Auditoria in Edmonton and Calgary, Alberta. Design: Public Works of Alberta, R. Clarke, chief architect; acoustical design and testing: Division of Building Research, National Research Council of Canada in collaboration with a design group of the Alberta Department of Public Works. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

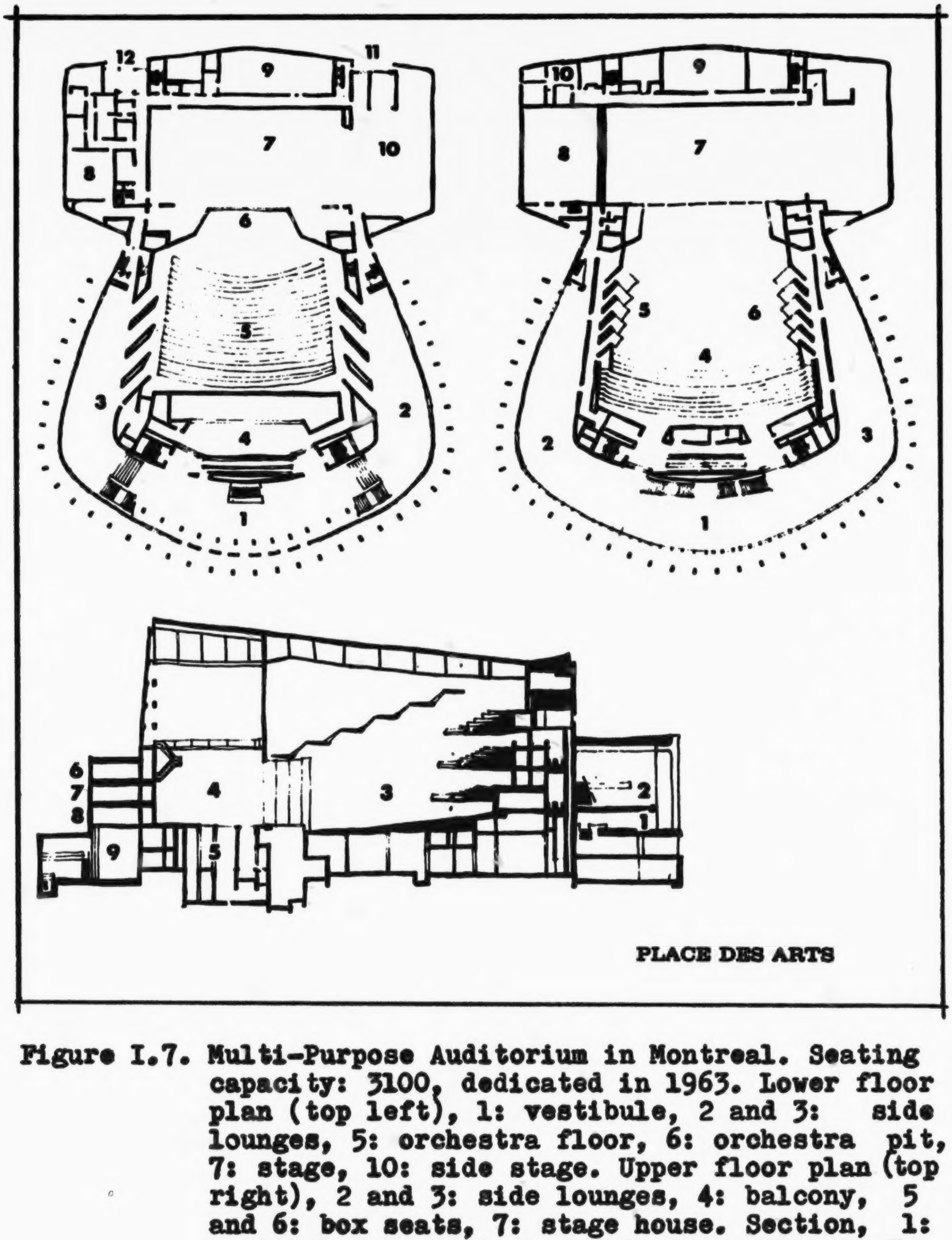


Figure I.7. Multi-Purpose Auditorium in Montreal. Seating capacity: 3100, dedicated in 1963. Lower floor plan (top left), 1: vestibule, 2 and 3: side lounges, 5: orchestra floor, 6: orchestra pit, 7: stage, 10: side stage. Upper floor plan (top right), 2 and 3: side lounges, 4: balcony, 5 and 6: box seats, 7: stage house. Section, 1: vestibule, 3: auditorium, 4: stage house, 5: elevator machine room. Affleck, Desbarats, Dimakopoulos, Lebensold, Michaud and Size, architects; Bolt, Beranek and Newman, and N. J. Pappas and associates, acoustical consultants. (Reprinted from Can. Arch., Nov. 1963).

Auditorium should be reduced to a minimum in order to preserve the genuine acoustical environment of the film as recorded on the sound track and as reproduced by the loudspeaker behind the screen. This goal will be achieved by providing a relatively short R.T. in the Cinema Auditorium, as recommended in Figure F.3. The R.T., however, should not be too short, because this would render the Auditorium "dead", necessitating excessive acoustical power from the loudspeaker and resulting in annoying loudness in the front and central seats (I-77, GB-52, GB-53).

Favorable hearing conditions will be achieved in Motion Picture Theaters by the following room acoustical measures, in addition to the previous recommendations outlined in Sections F and G (I-77, I-79, I-81, I-82, I-83, I-84, I-88, I-89, I-91, I-94, I-95, I-97, GB-52, GB-53):

(a) by keeping the R.T. as close as possible to the optimum value (Figure F.3);

(b) by keeping the volume per seat value within the low 110 to 150 ft^3, preferably closer to the lower value;

(c) by using overhead reflectors above the screen and keeping the entire ceiling, or at least its principal central portion, reflective;

(d) by ramping the audience floor steeply toward the rear in order to provide clear sight lines for the entire audience, thereby providing for an ample supply of direct sound;

(e) by adequately elevating the screen and the loudspeaker so that the entire audience will be well covered by the sound beam;

(f) by treating acoustically those boundary surfaces which are liable to produce echoes, long-delayed reflections, sound concentrations, etc. These harmful sound reflections are particularly noticeable in a relatively "dead" room, such as a Motion Picture Theater;

(g) by eliminating parallelism between reflective surfaces close to the screen and making the wall behind the screen absorbent if too long-delayed reflections are expected from this surface;

(h) by avoiding an excessive room length (above about 150 ft), partly to obviate the need for excessive acoustical power of the loudspeaker and partly to prevent lack of synchronism between sight and sound at the remote seats;

(i) by excluding overly deep balconies;

(j) by keeping a proper distance between the screen and the first row; this distance depends on the width of the screen;

(k) by installing heavily upholstered seats to counteract detrimental room acoustical effects of widely fluctuating audience attendance (the audience being very absorptive);

(l) by using an efficient absorbent treatment on the floor between the screen and the first row of seats in order to prevent reflections coming from directions other than the loudspeaker.

The provision for stereophonic sound reproduction in Motion Picture Theaters can be expected in the foreseeable future. This will require a particularly meticulous approach to the acoustical design of Motion Picture Theaters, affecting room shape, R.T., distribution of acoustical treatments, layout of the sound system, etc. (I-77, I-79).

A somewhat higher noise level can be tolerated in Motion Picture Theaters than in other types of rooms because of the higher sound level produced by the loudspeaker.

The noise originating from the projection booth is often a source of nuisance, particularly for those seated close to the projection booth. The penetration of this noise into the audience area can be prevented, as follows (I-77):

(a) by treating interior surfaces of the projection booth with efficient sound absorbing and also fireproof materials;

(b) by using double glazings in the projection and observation portholes; the glass panes should be of different thicknesses and hermetically sealed in their frames;

(c) by using a partition wall of adequate sound insulation between the Cinema Auditorium and the projection room (discussed in subsection S.1).

Figure I.8 illustrates floor plans and section of the Alhambra Cinema in Mannheim, West Germany (I-79).

Figure I.9 compares longitudinal sections of three outstanding European Motion Picture Theaters (GB-42).

I.4 Open-Air Concert Platforms, Open-Air Theaters, Drive-In Theaters

Contemporary architecture really cannot boast of any remarkable progress in the design of Open-Air Theaters since this type of Auditorium was first built by the Greeks and Romans, except that the masks, worn by the ancestors of the performers in order to reinforce their voice power,are being replaced by electronic sound systems.

Open-Air Theaters are used equally for spoken programs (live stage presentations) and for musical performances (concerts, musicals, etc.). If no sound amplification system is in operation, a musical performance, due to the higher inherent acoustical power of the instruments, will permit a much larger audience capacity than a spoken program (I-99, I-100).

Since the natural reinforcement of the direct sound from nearby reflective surfaces can be accomplished only to a very limited extent, a reduction of about 6 dB can be expected in the intensity of the sound every time the distance from the source is doubled (discussed in subsection C.9). To counteract this exces-

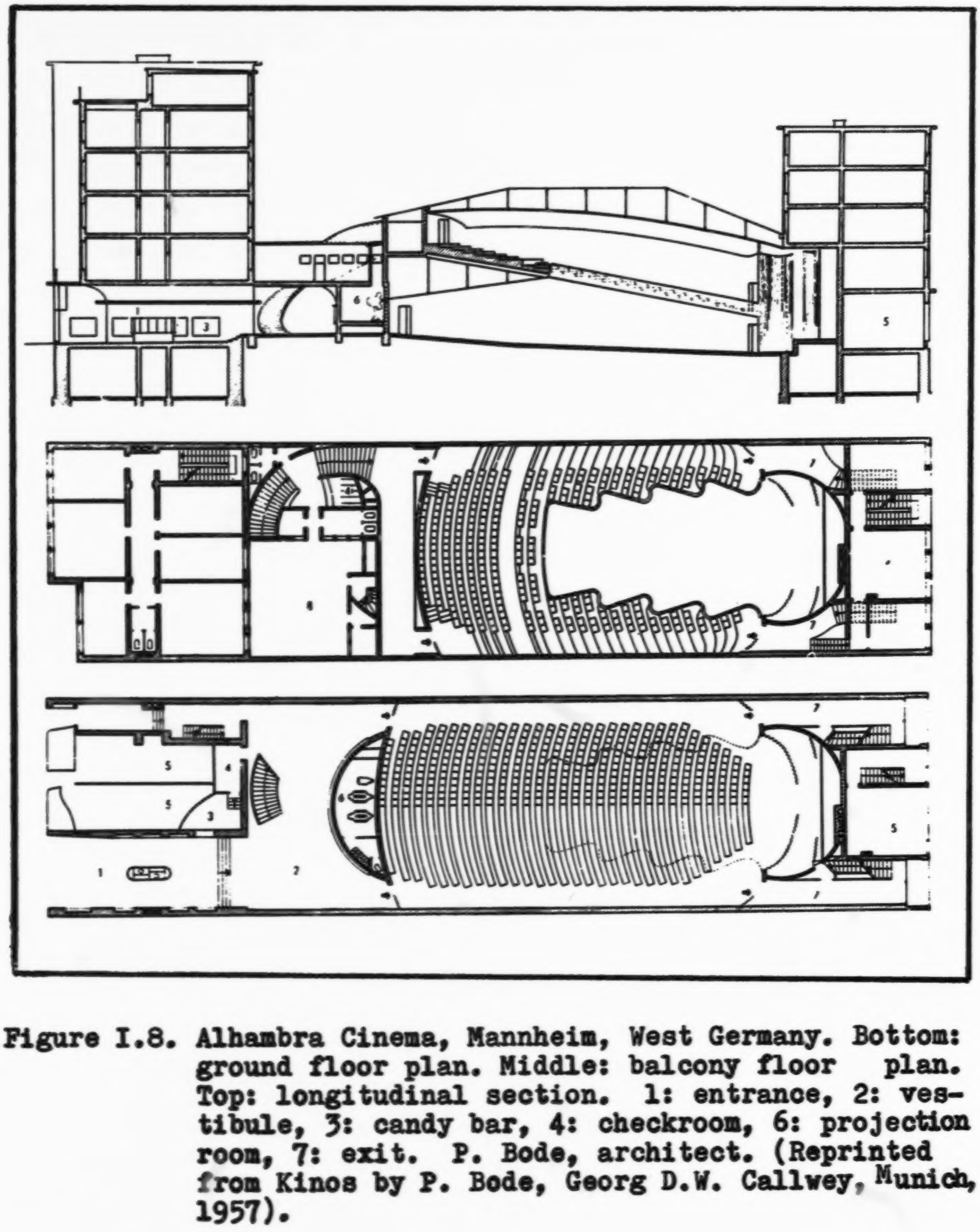


Figure I.8. Alhambra Cinema, Mannheim, West Germany. Bottom: ground floor plan. Middle: balcony floor plan. Top: longitudinal section. 1: entrance, 2: vestibule, 3: candy bar, 4: checkroom, 6: projection room, 7: exit. P. Bode, architect. (Reprinted from Kinos by P. Bode, Georg D.W. Callwey, Munich, 1957).

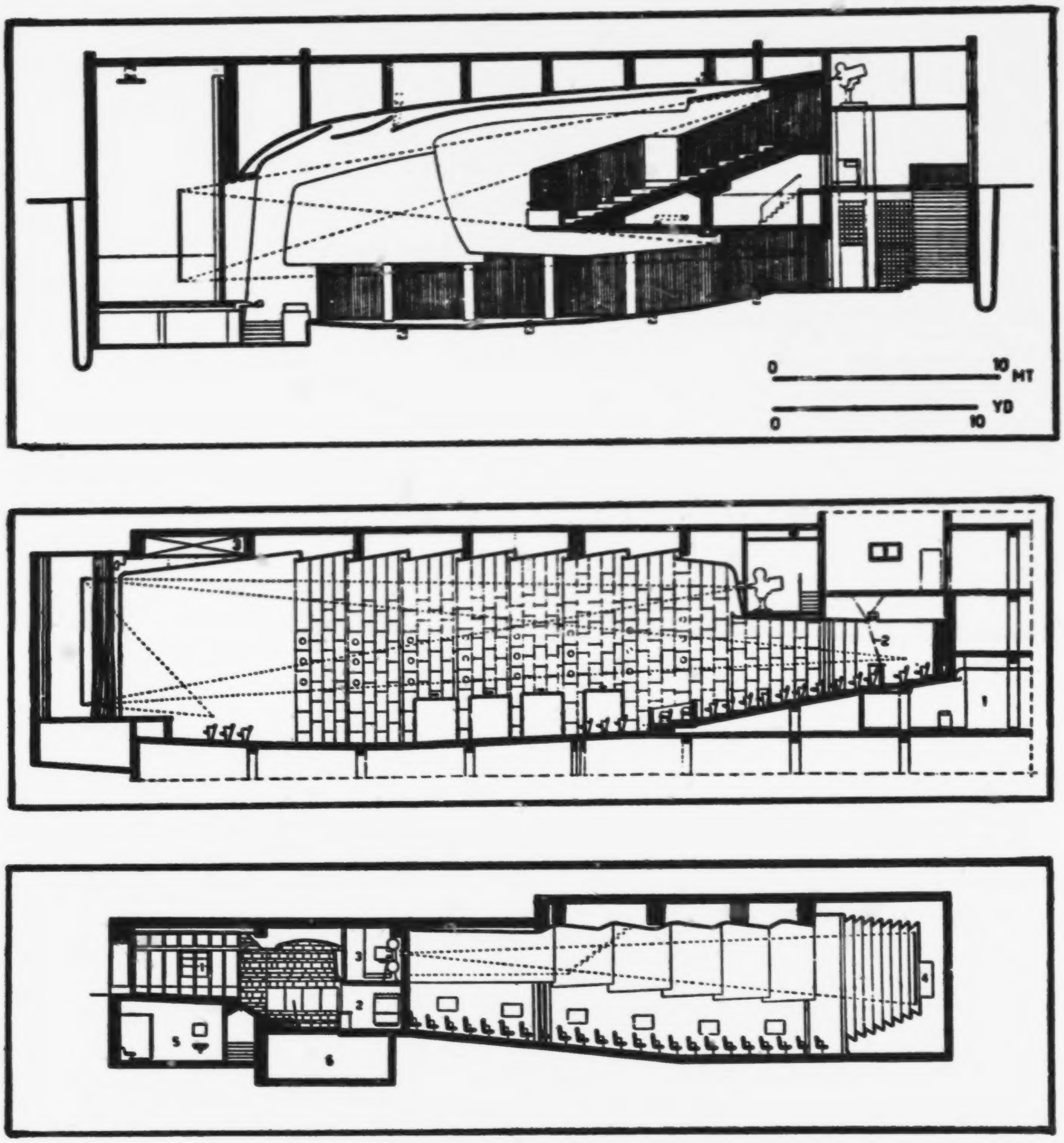


Figure I.9. Longitudinal sections of outstanding Motion Picture Theaters. Top: Elios Cinema, Geneva, Italy. L.C. Daneri, architect. Middle: UFA Cinema, Essen, West Germany. H. Klüppelberg and G. Lichtenhahn, architects. Bottom: Cinema Etoile, Zurich, Switzerland. W. Frey, architect. (Reprinted from Architetture Per Lo Spettacolo by R. Aloi, Ulrico Hoepli, Milano, 1958).

sive drop of sound intensity in the open air, attention should be given to following recommendations (I-99, I-100, I-101, I-104, I-109, I-113, I-114, GB-52, GB-53):

(a) the site should be carefully selected in view of the effects of the various topographical and atmospherical conditions (wind, temperature, etc.), and of exterior noise sources upon the propagation of sound;

(b) the basic shape, size and capacity of the seating area should be so determined that it will secure satisfactory speech intelligibility throughout the entire audience area. The distance of seats from sound source should be kept at a reasonable minimum, employing strict economy in the layout of aisles and gangways;

(c) an attempt should be made to accommodate the maximum amount of reflective surfaces close to the sound source. The use of a reflective and diffusive enclosure (band shell), that will direct the reflected sound waves both toward the audience and back to the performers, will be of great advantage around the platform (I-105, I-107, I-110, I-112). A paved space or an artificial streamlet, or other reflective surfaces, between stage and audience will effectively improve hearing conditions (I-111);

(d) the platform should be well elevated and the seating area steeply banked, with increased rake toward the rear, to provide the maximum amount of direct sound for the entire audience;

(e) converging back reflections to the platform from the backs of the concentric benches, particularly noticeable with partially or totally unoccupied seating area, should be eliminated;

(f) nearby reflective surfaces of existing buildings should be carefully checked against echoes or harmful reflections.

Many of the recommendations contained in Sections F, G and H will also apply to Open-Air Theaters if followed sensibly.

If audience capacity exceeds about 600, a high quality sound amplification system should be installed; its layout and volume should be such that the audience will be unaware of its existence (I-77, I-78, I-79).

Figure I.10 shows the plan of the Open-Air Theater at Red Rocks, Colorado, that has been designed with consideration for the principles discussed in this subsection (I-103, GB-42).

Figure I.11 presents the layout of a Drive-In Theater (GB-42). The sound system applied in this kind of Open-Air Theater sets no limit to the size of the audience area, as long as viewing is satisfactory (I-102, I-106, I-108).

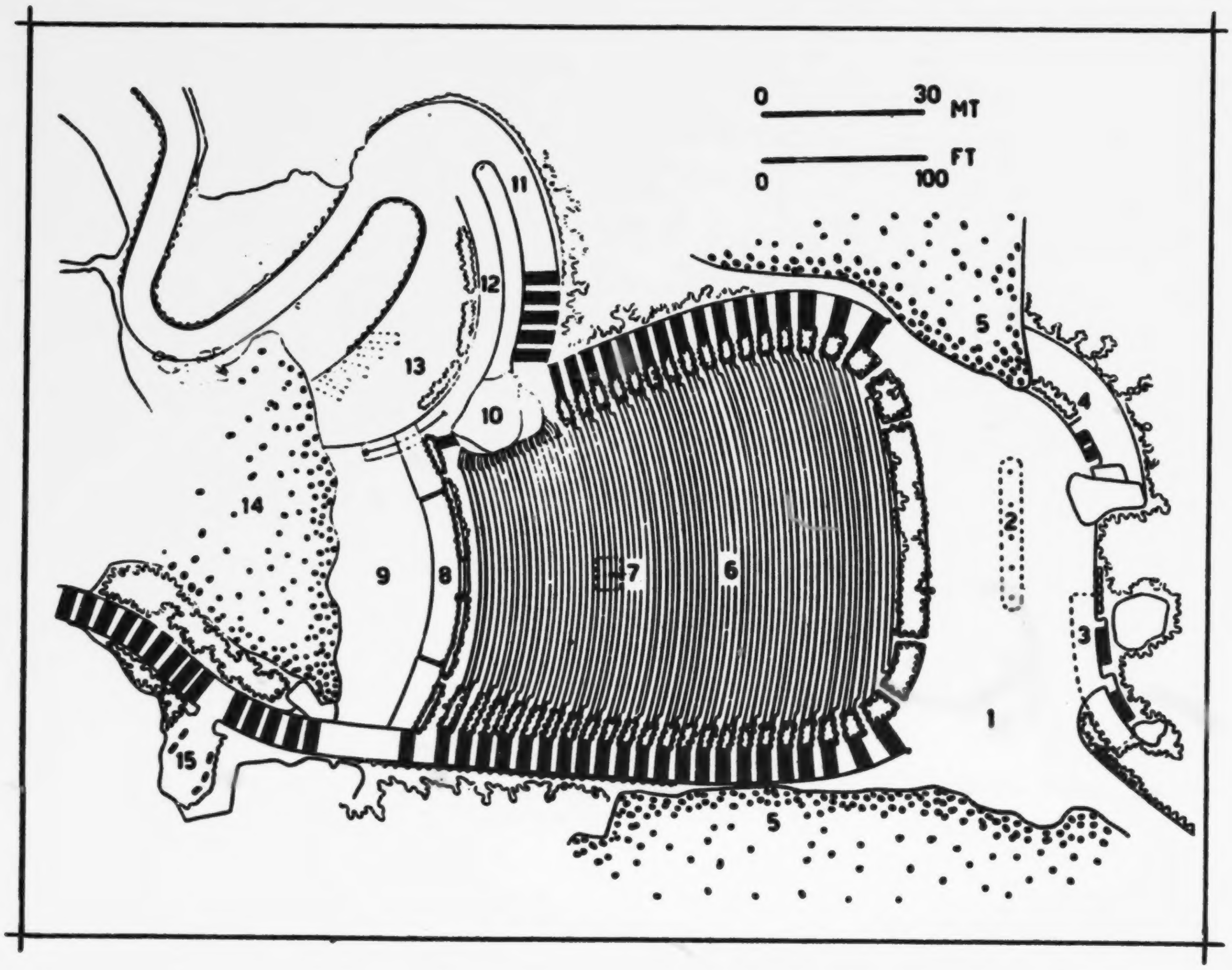

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Figure I.10. Open-Air Theater in Red Rocks, Colorado. 1: entrance, 2: box office, 5: high rocks, 6: audience area, 7: projection booth, 8: orchestra pit, 9: stage, 10: rock, 11: access, 12: ramp, 13: service yard, 14: rock, 15: terrace. B. Hoyt, architect. (Reprinted from Architetture Per Lo Spettacolo by R. Aloi, Ulrico Hoepli, Milano, 1958).

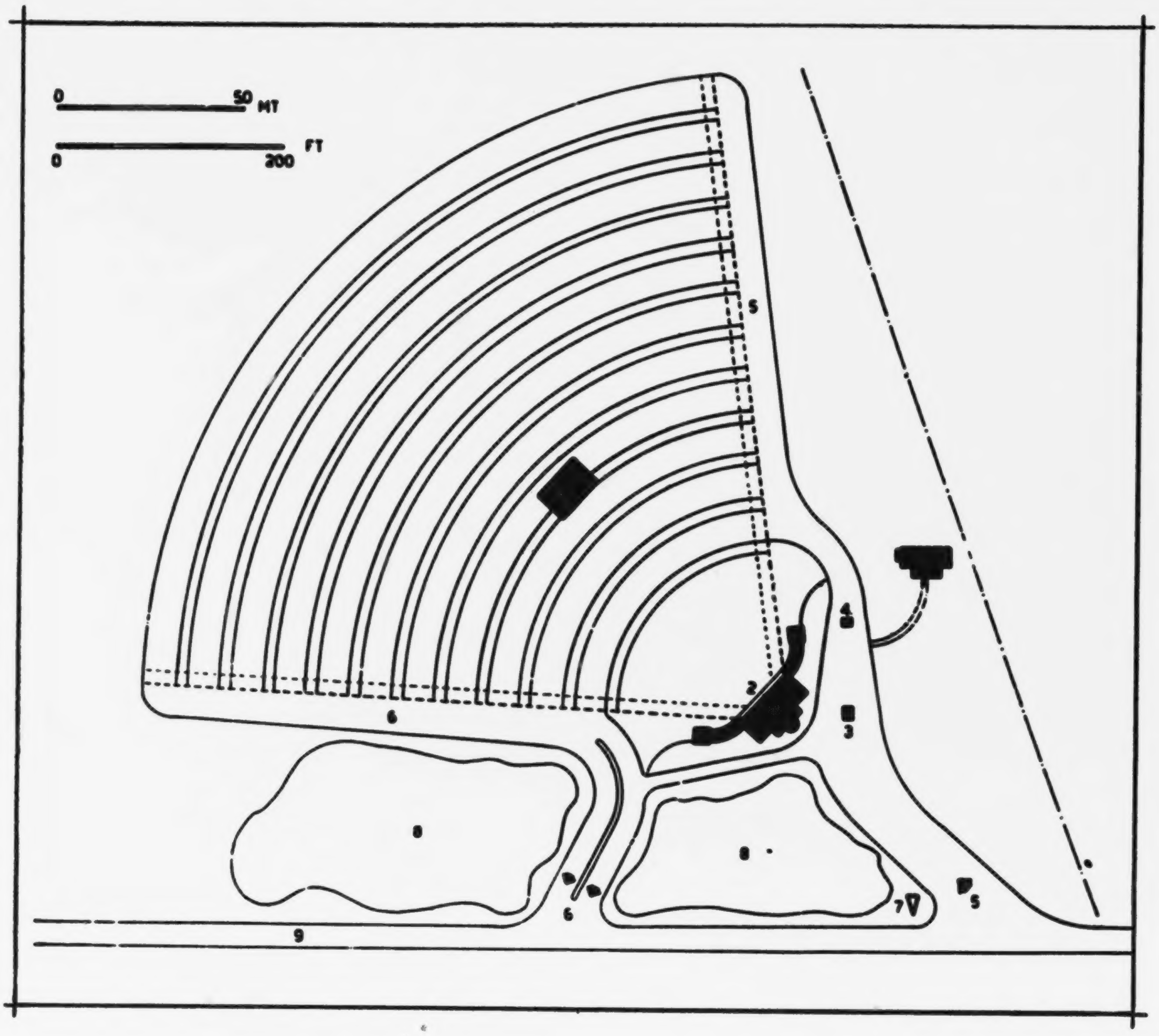

Figure I.11. Site plan of a Drive-In Theater in Rome, Georgia. 1: projection room, 2: screen, 3: candy bar, 4: ticket box, 5: entrance, 6: exit, 7: advertising sign, 8: lakes, 9: highway. McKendree, Tucker and Howell, architects. (Reprinted from Architetture Per Lo Spettacolo by R. Aloi, Ulrico Hoepli, Milano, 1958).

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(See list of abbreviations on page 1)

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Section J. Acoustical Design of Studios

- J.1 Acoustical requirements in Studio design
    - J.1.1 Optimum size and shape
    - J.1.2 Optimum reverberation characteristics
    - J.1.3 Diffusion
    - J.1.4 Noise control
- J.2 Radio Studios
- J.3 Television Studios
- J.4 Control Rooms
- J.5 Motion Picture Studios and Recording Rooms
- J.6 Listening Rooms
- References

The design of rooms used primarily for microphone pick-up is a special subject which is governed, in the main, by purely technical aspects (J-1, J-2, J-4, J-5, J-108, J-112, GB-52).

In addition to the general acoustical principles and recommendations discussed in preceding Sections, which are equally applicable to Studio design, the room acoustical requirements have to be met with greater precision, and a particularly high degree of isolation must be provided against extraneous noise and vibration (J-1, J-4, J-29, J-49, J-76, J-112). Pertinent acoustical calculations are applied to a wider frequency range than normally, i.e., from 62 cps usually up to 8000 cps (J-4, J-90).

This meticulous approach in Studio acoustics is necessary because of the substitution of the human (binaural) listener in the Studio by the microphone, a most sensitive electronic instrument which picks up the sounds in very much the same way as a person would do with monaural hearing. The microphone will indicate clearly (a) if reverberation characteristic is not optimum over a wide frequency range, (b) if diffusion is not high enough, (c) if any acoustical defect such as echo, room resonance, sound concentration, etc.,is noticeable, and (d) if the faintest noise or vibration exists in a Studio (J-1, J-4, J-49, J-76, J-90).

J.1 Acoustical requirements in Studio design

Studios form an important acoustic link between sound source and microphone (J-49, J-76). In their design, therefore, particular attention must be given to the following requirements, in addition to the recommendations dealt with in Sections F, G and H:

(a) an optimum size and shape of the Studio must be established;

(b) optimum reverberation characteristics must be provided;
(c) high degree of diffusion must be secured; and
(d) noises and vibrations must be completely eliminated.

These aspects are considered in following paragraphs.

J.1.1 Optimum size and shape

The size of a Studio is determined (a) by the physical space required for its occupants, equipment, and furniture, (b) by the function for which the room is to be used, and (c) by acoustical requirements (J-1, J-2, J-4, J-12, J-23, J-29, J-40, J-47, J-49, J-52, J-56, J-66, J-67, J-69, J-76, J-88, J-90, J-108, J-112).

The smallest dimension should be not less than about 8 ft. A Studio of minimum size should be acoustically "dead" down to the lowest frequency in order to avoid the harmful effects of room resonance (subsection D.6).

In establishing the necessary floor area for a Music Studio, even though a single instrumentalist occupies only about 6 to 10 ft^2 net floor area, it will be found that a total average of about 15 to 20 ft^2 floor space is required for each musician in a small Music Studio and about 20 to 40 ft^2 floor space in a large Studio. The extra space is taken up by circulation, music stands and by microphone placing. An average floor area of 4 to 6 ft^2 is required for singers depending on whether they are standing or seated. If audience "participation" is required in the Studio, a separate floor area must be set aside for audience seating. Table J.1 shows minimum volumes of Music Studios required by the BBC (J-4, J-112).

Table J.1. Minimum volumes for Music Studios required by the BBC

No. of performers	Minimum Studio volume, ft^3	Volume per performer, ft^3
4	1,500	375
8	4,000	500
16	12,000	750
32	30,000	940
64	82,000	1280
128	220,000	1720

The adoption of specific room proportions will contribute to a relatively uniform distribution of the normal modes at the lower end of the audio-frequency range so that no objectionable grouping of the resonant frequencies will occur (J-1, J-4, J-17, J-29, J-35, J-41, J-49, J-55, J-76, J-77, J-86, J-88, J-92, J-108, GB-52).

There are no room proportions that are universally recommended as optimum (discussed in subsections D.6 and F.3). For rectangular Studios the following room proportions are generally advocated (J-1, J-4, J-112, GB-52):

	height	: width	: length
small Studios	1	1.25	1.60
medium size Studios	1	1.50	2.50
Studios with relatively low ceiling	1	2.50	3.20
Studios with excessive length relative to their width	1	1.25	3.20

It must be stressed that the significance of room proportions in Studio acoustics diminish if the following conditions are fulfilled: (a) the Studio has a floor shape other than rectangular, (b) ideal reverberation characteristics have been achieved, (c) acoustical finishes are evenly distributed, (d) a high degree of diffusion has been provided, and (e) the volume of the Studio is above about 25,000 ft^3.

Boundary surfaces must be carefully checked against echoes, flutter echoes, and sound concentrations. Parallel surfaces must be eliminated (particularly in medium and large size Studios), or treated with acoustical materials highly absorptive throughout the frequency range between 62 and 8000 cps (J-1, J-49).

J.1.2 Optimum reverberation characteristics

Optimum reverberation times for Studios are generally shorter than those for Auditoria in which the sound program is perceived by binaural listeners (J-1, J-4, J-29, J-74, J-76).

Figure J.1 shows preferred ranges of optimum reverberation times vs. frequency for small, medium and large Studios, recommended by L.L. Beranek (J-76), and based partly on the studies of W. Kuhl (J-71, J-72). The shaded areas indicate the tolerances that may be permitted without causing noticeable differences to listeners in the quality of speech or music broadcasted. These R.T. values are in agreement with those previously shown in Figure F.3.

An optimum R.T. for a Studio is of vital importance to the final quality of sound; however, the apparent reverberation of a Studio, as eventually perceived by the listener, will depend also (a) on the pick-up technique (distance between sound source and microphone, number of microphones used simultaneously, etc.), and (b) on the quality of the microphone and in particular on

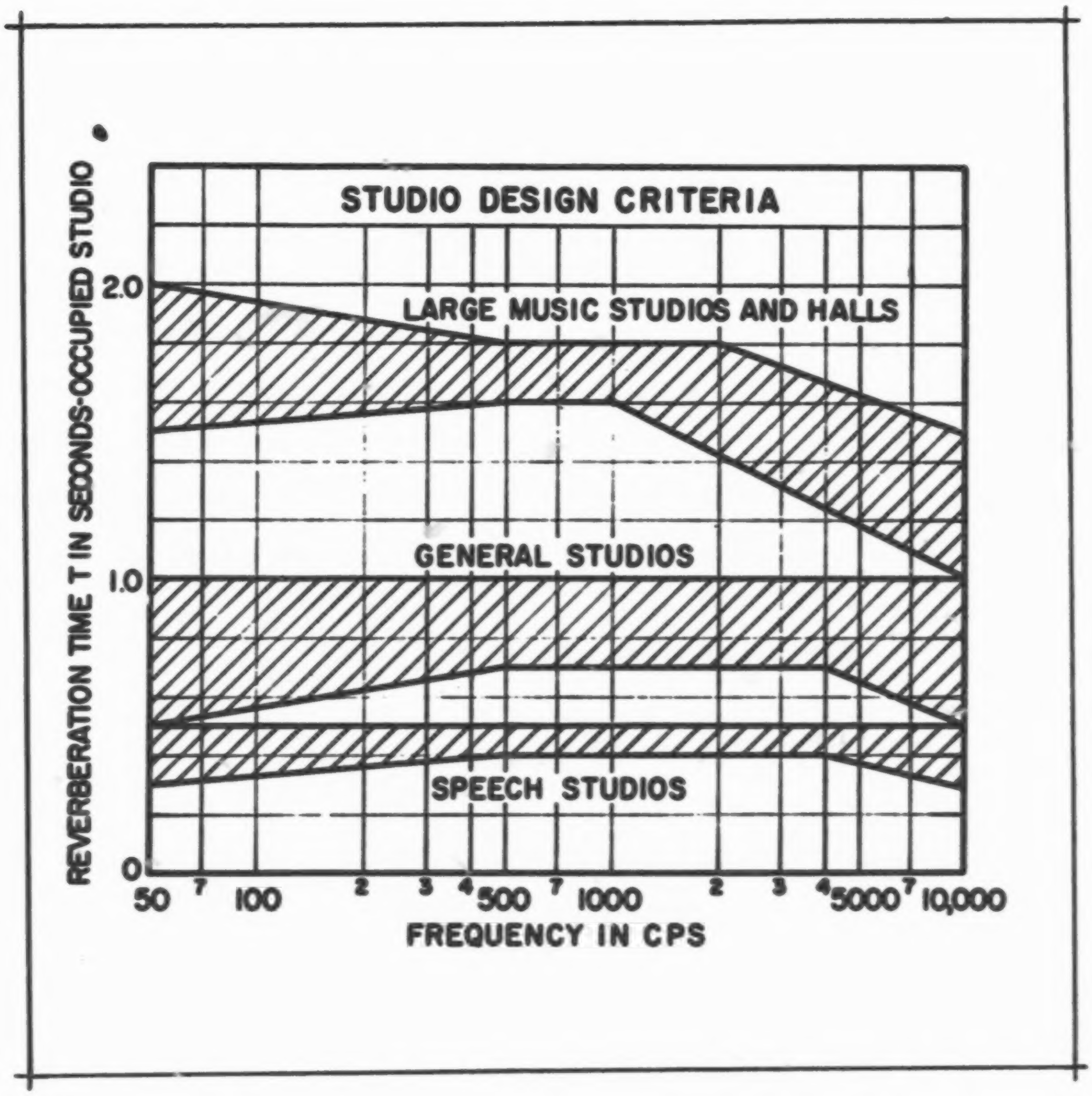


Figure J.1. Recommended reverberation time curves for Studios based on L.L. Beranek's experience, and on studies of W. Kuhl. (Reprinted from J. SMPTE, Oct, 1955).

its directional characteristics (J-1, J-4, J-7, J-23, J-29). The acoustical characteristics of the room in which the broadcasted or recorded sound is received or reproduced will also add to the apparent reverberation time (J-4, J-29).

It is essential that acoustical treatments, as required by reverberation calculations, should be uniformly and proportionately distributed over the three pairs of opposite enclosures of the Studio, except that low frequency absorbers should be in greater proportion on the end walls, i.e., those furthest apart (J-90). These recommendations are particularly important for small Studios.

Most broadcasting organizations prefer to have the acoustical treatments, wherever possible, installed in a manner that will allow temporary removal of the exposed finish treatment for later adjustment (tuning) if required. For the choice of suitable acoustical materials see subsection E.8.

Frequently Broadcasting and Recording Studios must be used for different programs, thereby requiring the provision for variable reverberation conditions, which can be achieved as follows:

(a) by variable absorbers on wall or ceiling surfaces; such as, hinged or sliding panels, rotatable cylinders, adjustable drapery, etc. (as outlined in subsection E.5 (J-22);

(b) by portable acoustic screens ("flats");

(c) by the use of a reverberation chamber (J-4); and

(d) by a special mechanism that controls the R.T. electronically and is operated in the Control Room (J-1, J-4).

J.1.3 Diffusion

The provision for a high degree of diffusion (discussed in subsections D.4 and F.4) is of vital importance in Studio acoustics. With good diffusion the number of those positions at which noticeable sound pressure variations occur are considerably reduced so that the microphone can be placed confidently in any convenient position of the room (J-1, J-4, J-49, J-76); in addition, a better balance between performers will be obtained (J-29).

Diffusion will be achieved (J-8, J-20, J-25, J-68):

(a) by the use of surface irregularities which project boldly into the air space of the Studio (e.g., cylindrical, spherical, prismatic or other irregular protuberances). The minimum projection of these surface irregularities must be about one-seventh of the wavelength of the sound to be diffused, i.e., for sounds down to 100 cps the projection must be at least 18" (J-4, J-20, J-90);

(b) by the alternate application of reflective and absorptive treatments;

(c) by random, non-symmetrical distribution of the various types of acoustical treatments (J-1, J-4, J-29, J-49, J-76); and

(d) by the elimination of parallelism between opposite surfaces (J-49, J-76, J-90).

Surface treatments or irregularities which are acoustically efficient but aesthetically lacking can always be hidden behind acoustically transparent grilles, such as perforated board, metal mesh, slats, etc. (J-112).

J.1.4 Noise control

This most important aspect of Studio acoustics is covered in subsection S.2 (J-1, J-4, J-11, J-12, J-29, J-40, J-47, J-49, J-56, J-76, J-88, J-96, J-112, J-129, J-134, J-135, GB-52).

J.2 Radio Studios

The following room elements must be integrated functionally and aesthetically into the architectural-acoustical design of Radio Studios (J-54, J-59, J-73, J-83, J-84, J-87, J-94, J-102, J-103, J-104, J-106, J-107):

(a) acoustical treatments and surface finishes to produce the required R.T.;

(b) mechanical and electrical fixtures; such as, grilles, lighting fixtures, speakers, statuslights, flicklights, clock, wiremoulds, outlets, etc.;

(c) seating, furniture, and permanently installed or portable equipment, as required to achieve the desired sound effect; such as, acoustic screens, turntables, sound effect equipment, etc.

Studios used for broadcasting purposes can be divided, quite arbitrarily, into the following types:

(A) Announce Booth. This is the smallest Studio, normally associated with a larger one. It is used for newscasts, narrations, commentaries, etc. It has a floor area of up to about 150 ft^2 (J-86). It is visually linked with the associated Studio by a large sound insulating observation window (discussed in paragraph N.3.5).

(B) Talk Studio. It is used primarily for newscasts, panel discussions, addresses, talks, and sometimes for recitals. It has a floor area of up to about 500 ft^2.

Particular care should be taken to avoid excessive low frequency reverberation or low frequency resonance in Announce Booths or Talk Studios; this can be accomplished by the use of efficient low frequency absorbers (J-29, J-58, J-61).

(C) Drama Studio. Its floor area covers from about 600 to 1500 ft^2, sometimes divided into two parts of contrasting acoustics by the use of moveable enclosures (folding panels or doors, curtains, etc.).

(D) Versatile Studio. Its floor area varies between about 1500 and 4000 ft^2. It is used equally for the spoken word and for musical presentations (J-15). Figure J.2 illustrates a Versatile Studio built in Lausanne, Switzerland.

(E) Audience Studio. Used for broadcasting the programs of symphonic orchestras and choirs (J-43), this large Studio is, in fact, a regular Concert Hall; consequently, the acoustical requirements and design principles discussed in Section H, "Acoustical Design of Rooms for Music" should be strictly adhered to (J-81, J-110, J-111, J-113, J-115). Besides other technical rooms, a Control Room and an Announce Booth are normally located adjacent to the Audience Studio, linked to one another by large sound insulating windows. The use of a sound amplification system is usually required to provide adequate sound coverage for the audience (J-1, J-4, J-29).

Table J.2 lists important architectural-acoustical data of outstanding Audience Studios (H-6, J-3, J-21, J-31, J-41, J-60, J-93, J-95, J-112, J-114).

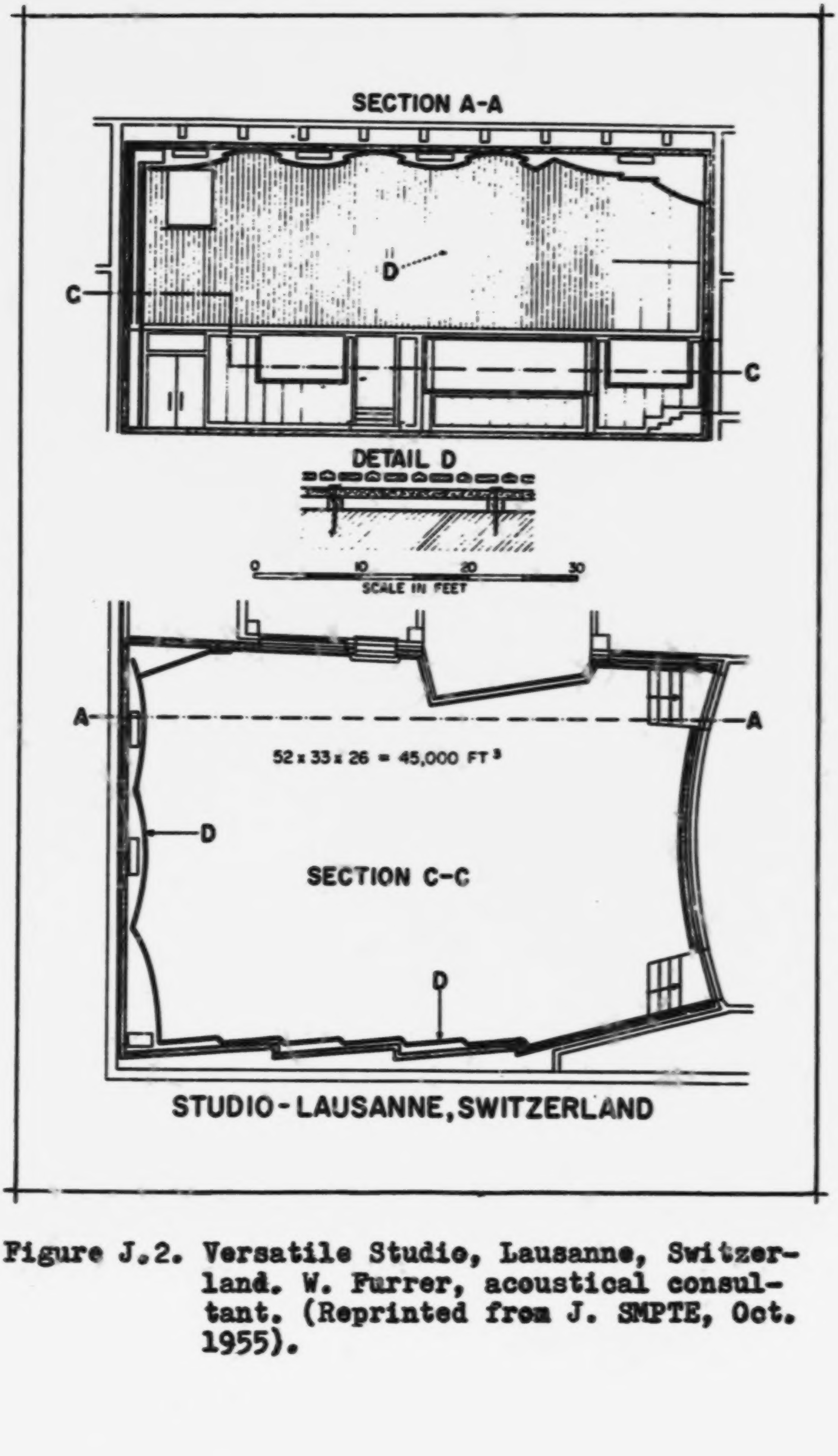

SECTION A-A
C
C
D
DETAIL D
0
10
20
30
SCALE IN FEET
A
A
52 x 33 x 26 = 45,000 FT³
D
SECTION C-C
D
STUDIO - LAUSANNE, SWITZERLAND

Figure J.2. Versatile Studio, Lausanne, Switzerland. W. Furrer, acoustical consultant. (Reprinted from J. SMPTE, Oct. 1955).

5

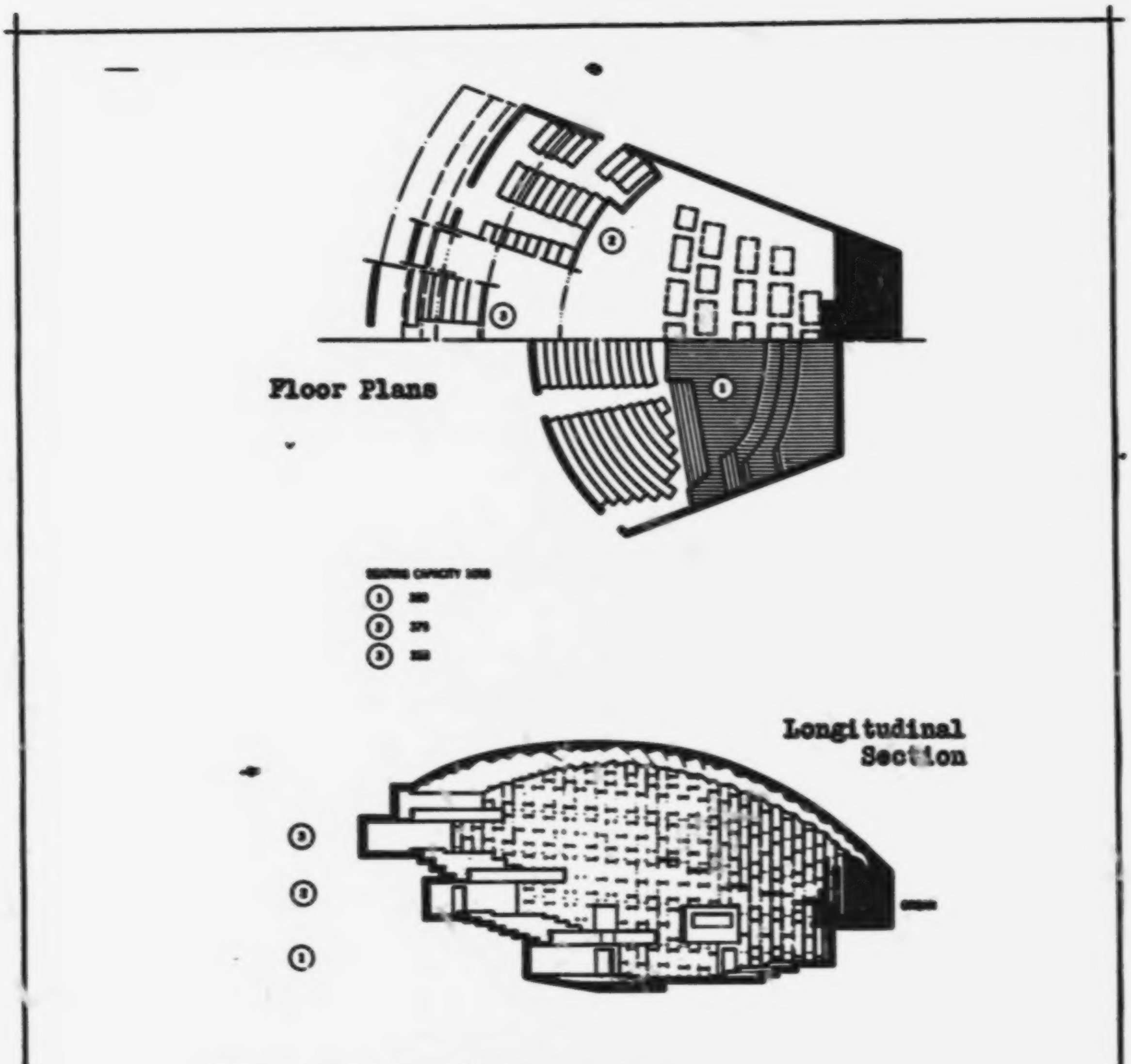
Table J.2. Architectural-acoustical data of outstanding Audience Studios

Name and year of dedication	Volume ft^3	aud. capacity if any	mid-fr. R.T. (full) sec
Audience Studio, Radio Free Berlin; 1959 (H-6, J-111, J-114)	455,700	1120	1.95
Audience Studio, Copenhagen Broadcasting House; 1945 (H-6, J-21, J-31, J-110)	420,000	1093	1.50
Audience Studio, North German Radio, Hanover; 1963 (J-60)	550,000	1350	1.70●
Audience Studio, Radio Austria, Vienna; 1936 (J-112)	200,000	390	1.50
Audience Studio, Stuttgart; 1959 (J-112)	160,000	350	1.20
Audience Studio, Baden-Baden; 1950 (J-112)	230,000	380	1.30
New Mutual-Don Lee Radio Studio, Hollywood; 1948 (J-41)	170,000	350	1.5
Audience Studio, Cologne Broadcasting House; 1953 (J-3, J-95)	240,000	720●	1.70

● estimated figures

Figure J.3 illustrates the fan-shaped Audience Studio of the Copenhagen Broadcasting House (H-6, J-21, J-31, J-110). A large number of Helmholtz resonators, made of plaster, and tuned to various frequencies below 100 cps, are distributed above the undulating ceiling of this large Studio (J-49).

Figure J.4 illustrates the Audience Studio of the North German Radio in Hanover.


Floor Plans
SEATING CAPACITY
Longitudinal Section
ORGAN

Volume: 420,000 ft^3 (11,890 m^3)
Volume per audience seat: 384 ft^3 (10.9 m^3)
Floor area per audience seat: 8.0 ft^2 (0.74 m^2)
Mid-frequency reverberation time: 1.5 sec
Year of dedication: 1945

FEET
METERS

AUDIENCE STUDIO, COPENHAGEN BROADCASTING HOUSE, DENMARK

Figure J.3. Audience Studio, Copenhagen, Denmark. V. Lauritzen, architect; V.L. Jordan, acoustical consultant. (Reprinted from Music, Acoustics and Architecture by L.L. Beranek, John Wiley and Sons, New York, 1962).

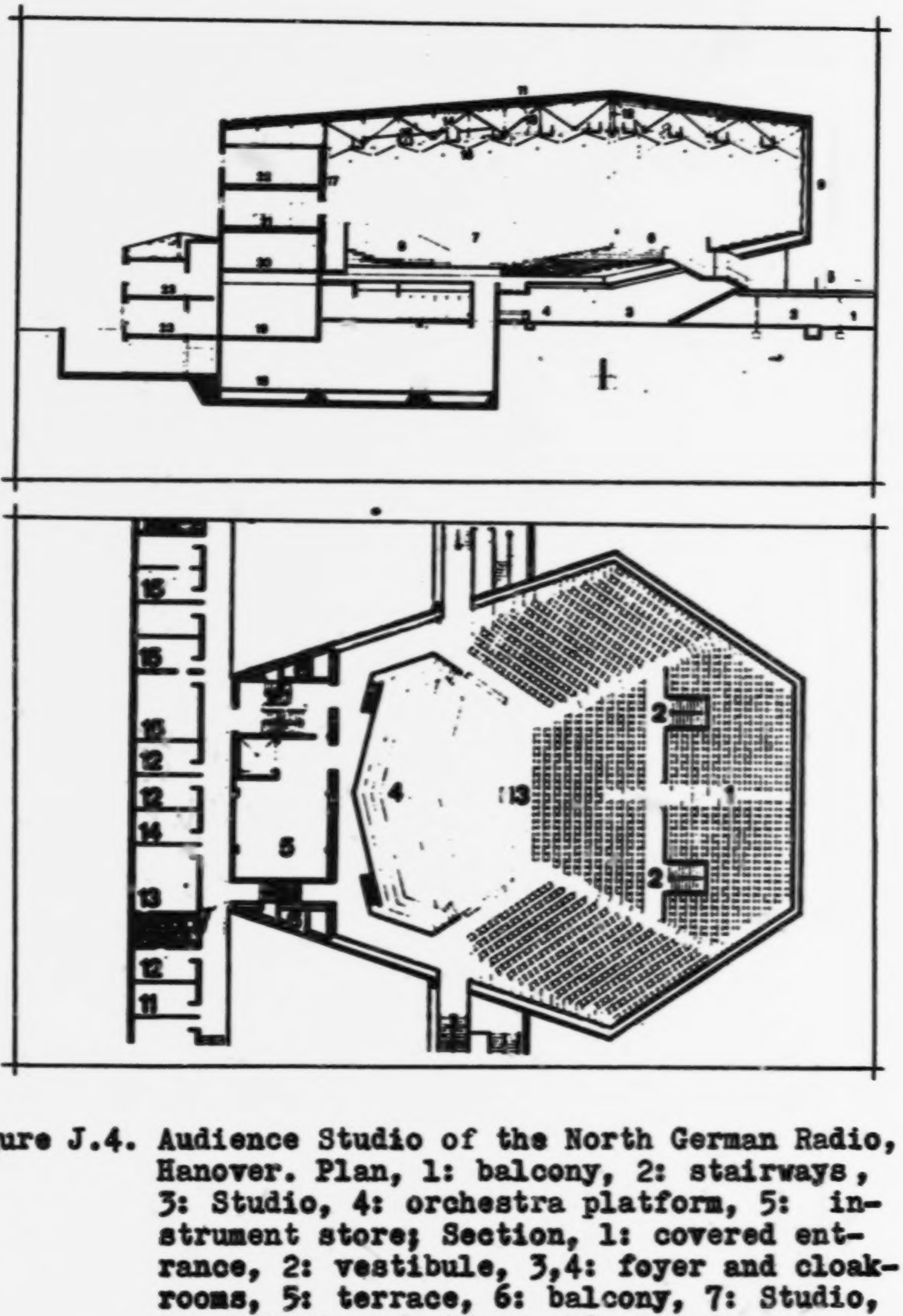


Figure J.4. Audience Studio of the North German Radio, Hanover. Plan, 1: balcony, 2: stairways, 3: Studio, 4: orchestra platform, 5: instrument store; Section, 1: covered entrance, 2: vestibule, 3,4: foyer and cloakrooms, 5: terrace, 6: balcony, 7: Studio, 8: orchestra platform, 10: low frequency absorber, 13: steel truss, 14: reflective panels, 15: catwalk, 16: lighting fixtures, 17: wood paneled wall. F.W. Kraemer and Ass., architects; W.Kuhl, acoustical consultant. (Reprinted from Bauen und Wohnen, Nov. 1963).

Radio Studios of various sizes are sometimes grouped into "suites" for special programs or purposes (J-4); such as,mixer suites, continuity suites, etc.

Figure J.5 shows the plan of the Oslo Radio House, containing all the types of Radio Studios listed in this subsection. The Audience Studio seats 200 listeners. Parallelism between opposite enclosures has been consistently eliminated in all of the Studios; this is a typical feature in the design of Scandinavian Radio Studios (J-32, J-49, J-70).

J.3 Television Studios

Acoustical conditions in Television Studios are not as critical as those in Radio Studios because the large amount of settings, scenery, properties, and décor, installed for the duration of a program, will change the original sonic environment of the Studio anyway (J-4, J-51, J-66, J-91, J-101, J-105).

Acoustical conditions are basically "dead" in a Television Studio (J-64); reverberation, if necessary, will be increased by the use of (a) appropriate settings, and properties, (b) moveable (portable) acoustical screens, and (c) artificial reverberation. If more reverberant acoustical conditions are required for the sake of the performers themselves, the portion of the television program requiring longer R.T. can be produced in an adequately reverberant Radio Studio, called "Satellite Audio Studio" (J-4, J-65, J-96).

Television Studios are constructed in various sizes, according to the required floor area and height. The main types are (J-4, J-66):

(a) "Theater" Studios with permanent audience seating; their area may be as large as 15,000 ft^2 and their volume about 500,000 ft^3;

(b) General-Purpose Studios, for all types of programs;

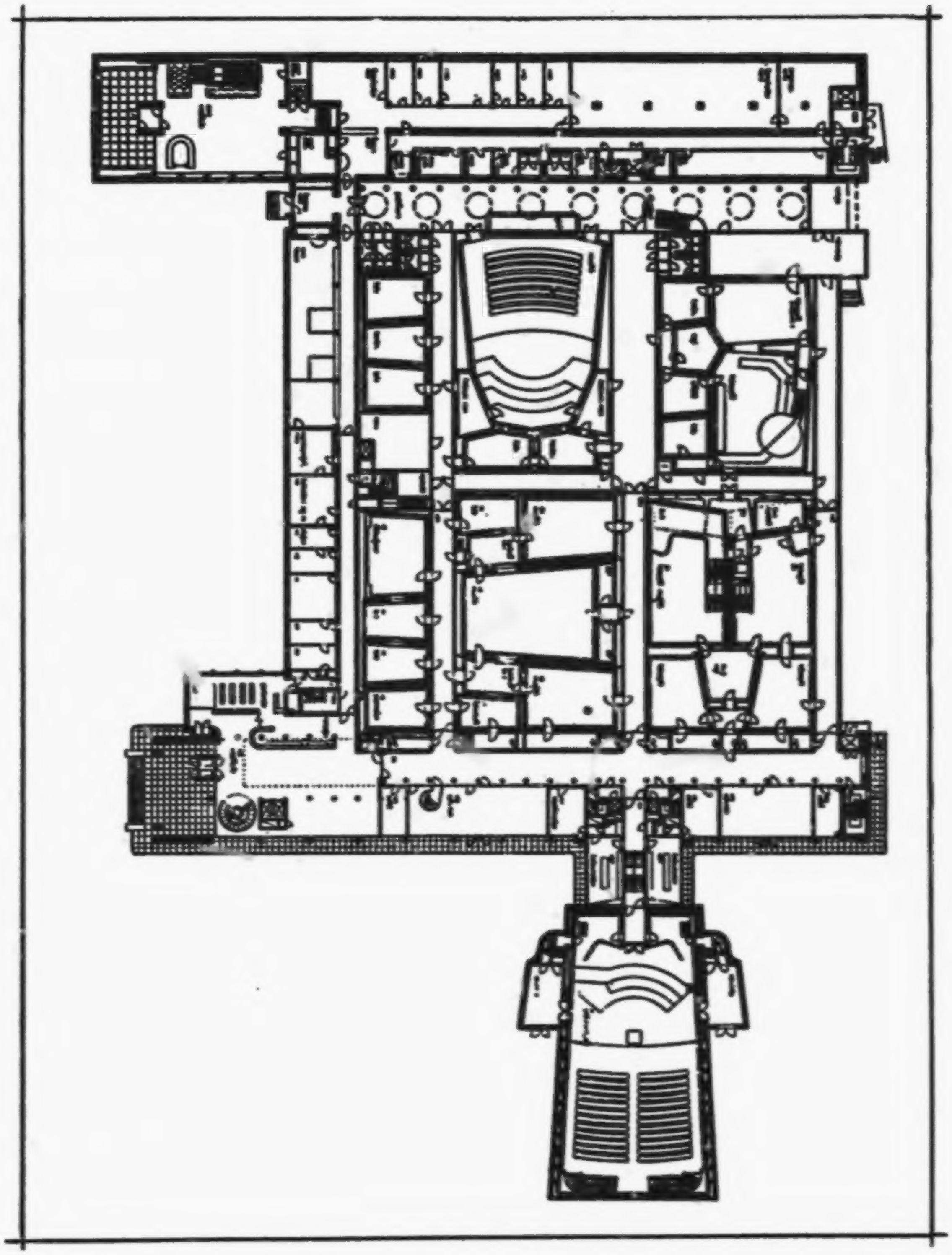


Figure J.5. Floor plan of the Oslo Radio House, Norway. N. Holter, architect; G. Nesheim, acoustical consultant. (Reprinted from Byggekunst, Jan. 1951).

(c) Small Interview and "Announcer" Studios;

(d) "Dubbing" suites.

A considerable clear height is usually required over the working area of the larger Studios to allow space necessary for the lighting grid with its system of catwalks and for flying the scenery (J-1, J-4, J-62, J-66, J-79).

Each Television Studio is normally provided with the following auxiliary rooms: Production (video) Control Room, with a required R.T. of about 0.25 sec; Sound (audio) Control Room; Lighting Control Room; Sound Effects Room; Announce Booth with a required R.T. of about 0.25 to 0.30 sec; and a number of various stores. The Control Rooms, usually grouped in a suite, are often located one story higher than the Studio floor (J-2, J-4, J-62, J-66).

In Television Audience Studios the use of a sound amplification system is indispensable if the audience is to receive adequate sound coverage.

Simple and inexpensive acoustical treatments are usually applied in Television Studios; such as, mineral wool blankets (covered with metal lath, wire screen, chicken wire mesh, or perforated board), wood wool slabs, etc. The required low frequency absorption can be obtained by using plywood, hardboard or plasterboard panels, which simultaneously form a suitable dado for the lower 6 to 8 ft high portion of the wall. Most of the wall treatment is eventually shielded by a cyclorama curtain spaced some 3 to 6 ft away from the wall, thereby providing adequate space for unobtrusive circulation along the perimeter of the Studio (J-4, J-42, J-51, J-66, J-75, J-96).

Figure J.6 shows the floor plans of a CBS Television Color Studio, built in New York.

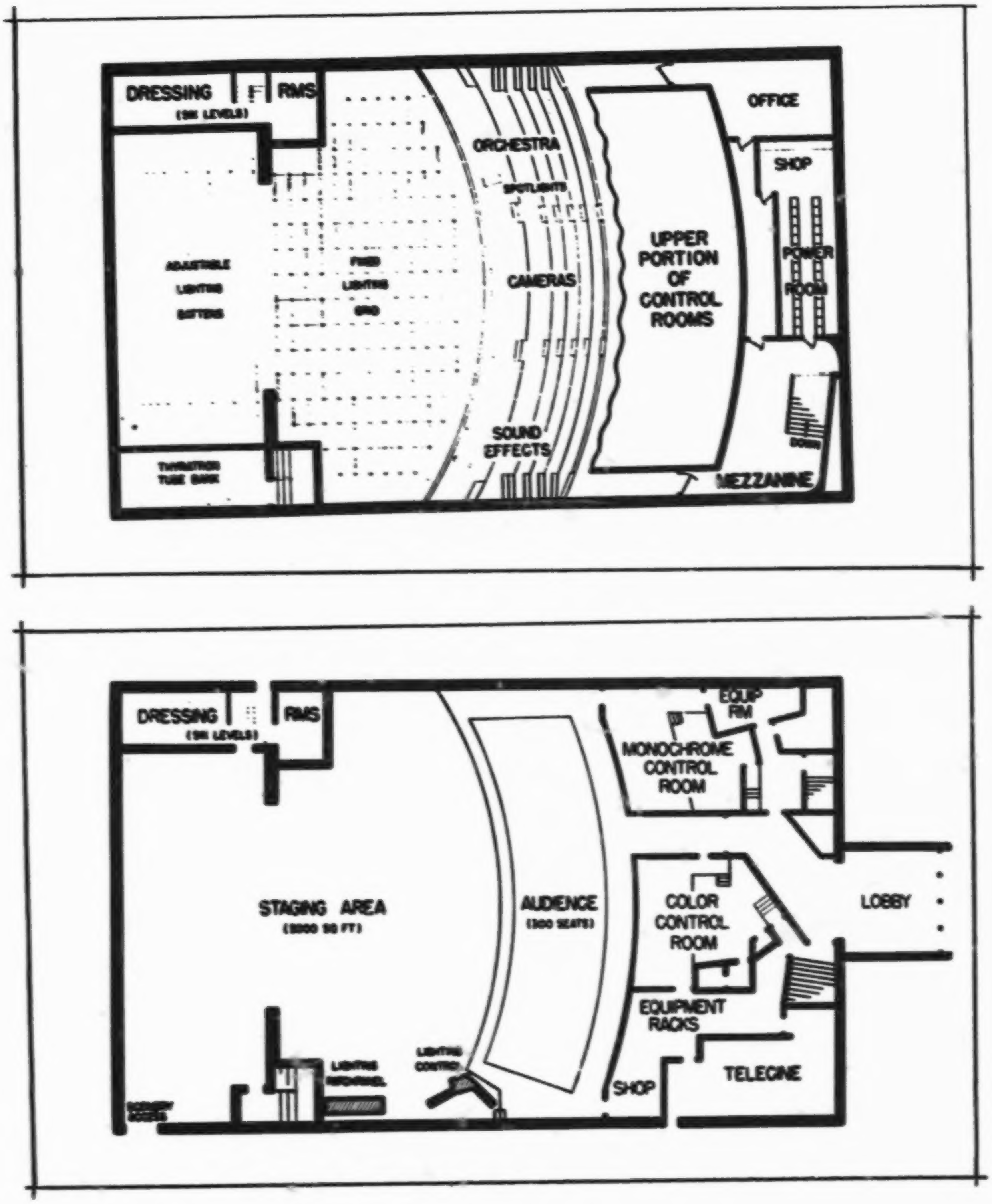

DRESSING
(SIX LEVELS)
RMS
ADJUSTABLE
LIGHTING
BATTENS
FIXED
LIGHTING
GRID
THYRATRON
TUBE BANK
ORCHESTRA
SPOTLIGHTS
CAMERAS
SOUND
EFFECTS
UPPER
PORTION
OF
CONTROL
ROOMS
OFFICE
SHOP
POWER
ROOM
DOWN
MEZZANINE
DRESSING
(SIX LEVELS)
RMS
STAGING AREA
(3000 SQ FT)
AUDIENCE
(300 SEATS)
LIGHTING
PATCHPANEL
LIGHTING
CONTROL
SCENERY
ACCESS
EQUIP
RM
MONOCHROME
CONTROL
ROOM
COLOR
CONTROL
ROOM
LOBBY
EQUIPMENT
RACKS
SHOP
TELECINE

Figure J.6. CBS Television Color Studio 72, New York, with lower floor plan (bottom), and upper floor plan (above). (Reprinted from J. SMPTE, Oct. 1955).

J.4 Control Rooms

Every Radio or Television Studio is linked with one or more Control Rooms, the visual contact between Studio and Control Room being provided by a wide control window with unobstructed view of the Studio floor. As long as the Studio floor area does not exceed about 800 to 1200 ft^2, Control Room and related Studio can be both located on the same floor level; Control Rooms linked with Studios of larger size need to be elevated accordingly (J-48).

The size and shape of the Control Room will depend on the furniture and technical equipment it has to accommodate; such as, audio console, monitoring and talkback facilities, disc reproducer, tape recorder and playback unit, clock, reverberation control unit, video monitor, intercom key panel, seats for the control personnel, etc.

The BBC recommends a R.T. of 0.4 sec at the 500 cps frequency in Control Rooms (J-88).

J.5 Motion Picture Studios and Recording Rooms

Motion Picture Studios are usually built as large halls with highly absorbent enclosures so that the sets can contribute their own acoustical characteristics as required (J-123, J-132).

The site for a Film Studio is chosen generally as a compromise between a quiet surrounding and reasonable accessibility (J-128, J-129). Economy in the construction and efficiency in operation suggests that several large size Motion Picture Studios be grouped together; this will allow set construction and preparation to be carried out in one or more Studios while normal production continues in the adjacent ones. The provision for the required short R.T. within these Studios and for a high degree of noise and vibration isolation are main objectives of the acoustical design (J-126).

Recording Studios (or Recording Rooms) are built quite similar to Radio Studios, with a "dead" acoustical environment (J-68, J-117, J-118, J-119, J-121, J-122). They are usually connected with a Control Room and other auxiliary rooms (J-131, J-135). Their floor area and shape will depend on the furniture and on the technical equipment they have to accommodate (disc recorders and reproducers, magnetic tape recorders and reproducers, loudspeakers, etc.). As a rule, no public is admitted to Recording Studios, consequently priority can be given to acoustical rather than aesthetic requirements; temporary changes may be made in their acoustical treatment irrespective of aesthetics and even a latitude in experimentation is possible (J-29, J-120).

J.6 Listening Rooms

They are used for checking records, discs, magnetic tapes and tape-editing,and monitoring of various sound programs. They are sometimes linked with a Radio or Television Studio by an observation window providing a wide view of the Studio floor (J-124, J-125, J-133). Acoustical conditions in Listening Rooms should resemble those of an average domestic living room (J-4, J-90, J-127), with a R.T. of about 0.4 to 0.5 sec. Their floor area and room shape will depend on the furniture and technical equipment to be accommodated (turntable, magnetic tape recorder, loudspeaker, etc.).

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relative to Section J: "Acoustical Design of Studios"

(See list of abbreviations on page 1)

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Section K. Checking the Acoustical Performance of an Auditorium

- K.1 Checking during the design
  - K.1.1 Control of reverberation characteristics
  - K.1.2 Graphic method
  - K.1.3 Model tests
- K.2 Checking during construction and after completion
  - K.2.1 Speech intelligibility testing
  - K.2.2 Test performances, test concerts
  - K.2.3 Objective measurements of acoustical properties

References

From the preceding Sections it becomes obvious that the necessity for a workmanlike sound control of relatively large and acoustically critical Auditoria is irrefutable. Their periodic evaluation,during their design and after their construction has started, is an integral part of their sound control.

The occasional checking of relatively small or seemingly insignificant Auditoria will also be necessary, and often will prove most helpful in the provision of favorable acoustical conditions for both listeners and performers.

A short discussion of the different methods of checking the acoustical performance of Auditoria, during their design and construction stages and after their completion, is given below.

K.1 Checking during the design

During the design stage of an Auditorium the architect obviously will be anxious to predict whether or not acoustical conditions in the completed room will serve satisfactorily the purpose that has been specified by the client. The methods mentioned here, if applied in due course and with precision, will foreshadow the acoustical performance of the Auditorium with a reasonable degree of engineering accuracy.

K.1.1 Control of reverberation characteristics

This can be achieved by the calculation of the R.T., as described previously in subsections D.5, F.5, G.3, H.3 and J.1.2.

K.1.2 Graphic method

The floor plans and building cross sections of Auditoria will offer a good opportunity to follow the paths taken by rays of sound which travel from the source to the listeners (GB-21, K-1, K-2). It has been assumed in subsection D.1 that these rays will be reflected from the boundary surfaces at an angle that is equal to the angle of incidence (law of reflection). This rather simplified graphic analysis of the propagation of sound in rooms will be very useful in revealing acoustical merits and faults of enclosed spaces (K-2, K-3, K-4, K-23, GB-21, GB-53). Such an analysis will be useful (see Figure K.1):

(a) to check whether or not the supply of direct sound to all parts of the seating area is satisfactory, i.e., whether or not seating area is adequately ramped or raked, and the sound source elevated;

(b) to ensure that sufficient sound reflections are provided for the entire seating area, in particular, that reflected sound increases progressively towards the remote seats (Figure K.1.A);

(c) to trace surfaces liable to produce acoustical defects; such as, echoes (Figure F.4), corner echoes (Figure K.1.B), long-delayed reflections (Figure K.1.C), sound concentrations (Figure K.1.D), or flutter echoes;

(d) to locate areas in acoustical shadow (Figures K.1.E and K.1.F).

Analyzing the paths of sound waves beyond the first and second reflections is a complex procedure, which, fortunately, is unimportant because of the loss of sound energy after several reflections (GB-43).

K.1.3 Model tests

Model tests, when applied, normally use optical or wave methods (K-1, K-2, K-3, K-4, K-8, K-14, K-17, K-18, K-19, K-21, K-22, GB-52).

In the first case, conditions of geometrical acoustics are assumed using wavelengths that are extremely small compared to the dimensions of the model (light distribution method, ray method, etc.). In the second case, calculations are based on wave-

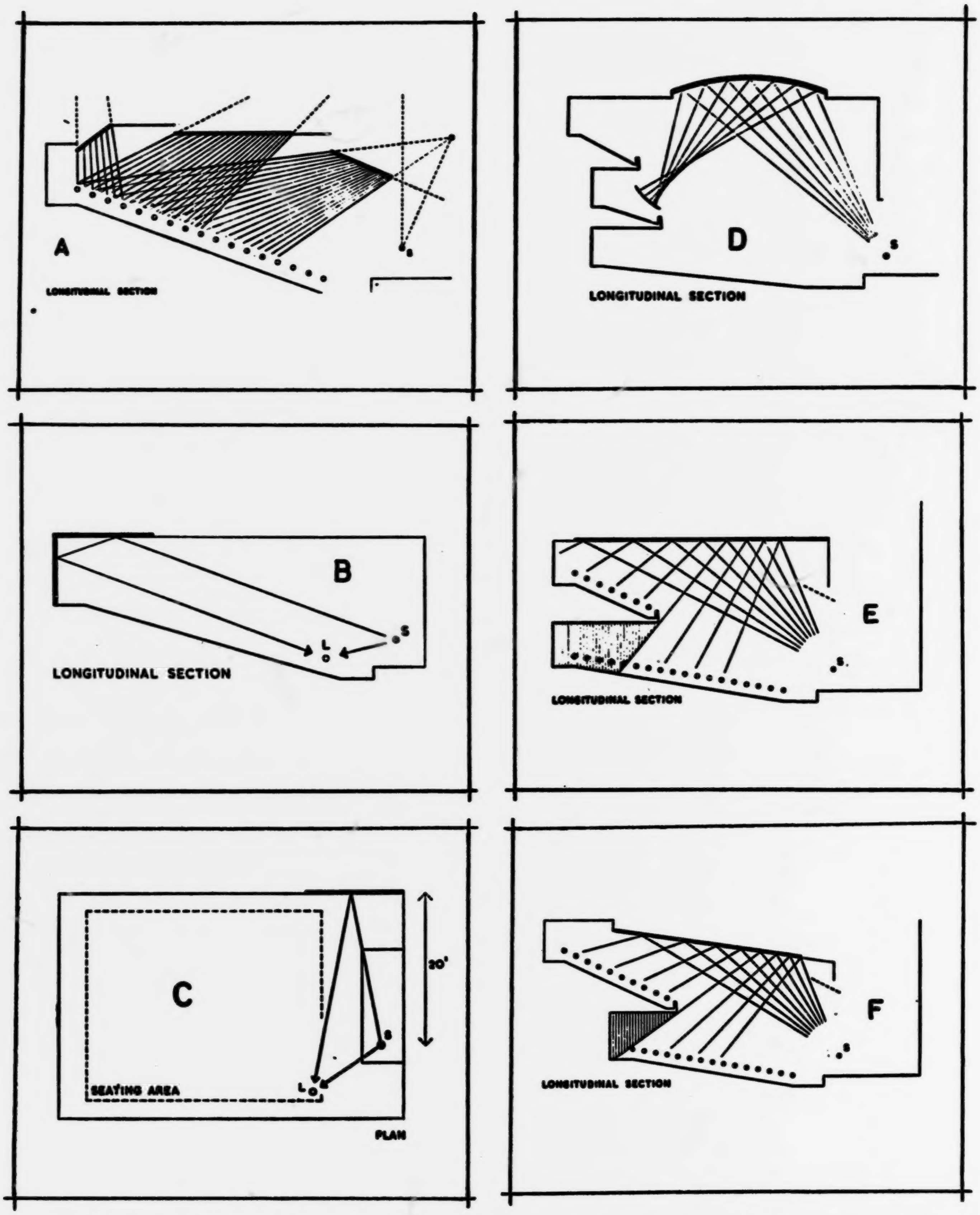
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Figure K.1. Graphic analysis as an important tool in checking the acoustical performance of an Auditorium. (Reprinted from Design for Good Acoustics by J.E. Moore, Architectural Press, London, 1961).

lengths reduced in the same proportions as the dimensions of the model (ripple tank method, ultrasonic method, sound pulse method, etc.)

K.2 Checking during construction and after completion

Before being declared completed and ready for use, every Auditorium should undergo certain tests to make sure that it has no acoustical defect that could impair its usage. This test will enable the architect to take immediate measures for the acoustical correction of the Auditorium if it proves to be necessary.

In simple cases the room can be checked for echoes or flutter echoes by producing a sharp hand clap at the location of the sound source and then by listening to the response of the room (K-1). Similarly,a person with an acute ear will quickly detect the reverberation characteristics of the room.

In medium and large size Auditoria, however, particularly if importance is attached to good acoustics, a quantitatively and qualitatively more precise evaluation of the acoustical properties is necessary. These will be described briefly in subsequent paragraphs.

K.2.1 Speech intelligibility testing

The intelligibility within a room used for speech can be determined by articulation or intelligibility testing. A speaker located on the stage or platform reads a number of meaningless monosyllables or meaningful words (phrases, sentences), and listeners at various parts of the seating area write down or repeat what they think they hear. The percentage of the words that is correctly written down or repeated is called percent articulation or percent intelligibility (K-1, K-2, K-15, GB-29, GB-41). The word "articulation" is used when the speech material consists of meaningless syllables or fragments; the word "intelligibility" is used when the speech material consists of meaningful, complete words, phrases or sentences (GB-73).

K.2.2 Test performances, test concerts

Before an Auditorium of particular acoustical importance comes into regular use, carefully planned test performances should be held to test the room subjectively for major acoustical faults; such as, echoes, flutter echoes, incorrect R.T., unusual lack of low frequency sounds, room resonance, etc. Any defect which might be found can then be further investigated and probably corrected before the official opening of the Auditorium,and while the building contractor is still on the site (H-6, H-49, H-108, I-51).

K.2.3 Objective measurements of acoustical properties

During construction and after completion of an Auditorium several acoustical characteristics, such as R.T., echoes, diffusion, balance of high, middle, and low frequencies, sound pressure level, noise level, etc., can be objectively measured or detected by instruments, thus providing a precise quantitative evaluation of the acoustical performance of the room (K-9, K-10, K-11, K-12, K-20).

Reverberation time measurements during the construction of a Radio or Television Studio might suggest certain adjustments or modifications in the planned acoustical treatment of the Studio (J-41). Acoustical measurements in completed Radio Studios will reveal whether or not any change is required in the acoustical treatments, and whether or not any difficulty will be encountered in microphone pick-up because of room resonance or overly delayed reflections (K-7).

The measurement of R.T., made at several positions and the results averaged, in a completed Auditorium is a basic criterion in the ultimate evaluation of its acoustical performance (K-6, K-13).

References

relative to Section K: "Checking the Acoustical Performance of an Auditorium"

(See list of abbreviations on page 1)

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Section L. Sound Amplification Systems

L.1 Principal uses of sound amplification

L.2 System components

L.3 Loudspeaker placing

References

It has been mentioned in preceding Sections that the sound level can be increased in the rear portion of an Auditorium if

- the shape and volume of the room are acoustically favorable,
- suitable reflective surfaces have been provided,
- R.T. is optimum,
- acoustical defects have been successfully eliminated, and
- disturbing noise has been banished from the Auditorium.

In large halls, however, even though attention has been given to these aspects, speech level often will be too low for satisfactory hearing conditions. In large Auditoria, therefore, and also in outdoor locations, a sound amplification system is nearly always necessary to secure adequate loudness and good distribution of sound (L-3, L-7, L-26, L-37, L-43, L-52, L-53, L-57).

It is not possible to specify the exact size or volume of small or medium size Auditoria above which a sound system is needed; this will depend on the acoustical conditions of the room, the strength of the voice of the speaker, the distance between speaker and listeners and on the ambient background noise in the room (L-7, L-37, L-53).

According to V.O. Knudsen and C.M. Harris, if a high degree of speech intelligibility is desired, a sound amplification system should be used in Auditoria exceeding a volume of about 50,000 ft^3; if the noise level is greater than 40 dB, a sound system may be necessary even in smaller rooms (L-3).

W. Furrer recommends the installation of a sound amplification system in Auditoria whose volumes exceed the following values (GB-52):

for the average speaker	105,000 ft^3
for the trained speaker	210,000 ft^3
for instrumentalists or vocalists	350,000 ft^3
for a large symphonic orchestra	700,000 ft^3
for a large choir	1,750,000 ft^3

According to L.L. Beranek (L-37), in an acoustically well designed Auditorium, a sound system will be needed if the room volume exceeds about 75,000 ft^3,and if the voice must travel more than about 80 ft to a listener. On the other hand, a sound amplification system may be required in Auditoria having a volume greater than about 15,000 ft^3 if the room is heavily treated with absorbing materials,and the distance between sound source and listeners exceeds 40 ft. Generally,a sound system will be needed for small rooms if they are too noisy (particularly in the frequency range corresponding to speech sounds), or if the room is extremely reverberant.

P.H. Parkin and H.R. Humphreys recommend a sound system for Auditoria accommodating more than 500 audience if the floor is flat,with some intruding noise. On the other hand, they claim that an acoustically well designed Theater with trained actors probably will not need a sound system unless its seating capacity exceeds 1500 (L-7).

L.1 Principal uses of sound amplification

Sound amplification systems are used for the following purposes (L-2, L-3, L-6, L-7, L-9, L-12, L-15, L-16, L-22, L-23, L-37, L-38, L-39, L-40, L-43, L-45, L-46, L-50, L-51, L-52, L-53, L-54, GB-38):

(a) to reinforce the sound level in an Auditorium or in outdoor locations when the sound source is too weak to be heard;

(b) to minimize room reverberation;

(c) to provide amplified sound for overflow audiences;

(d) to increase the sound level on the stage of an Auditorium in order to provide an adequate sound level for the performers or for listeners seated on the stage;

(e) to provide artificial reverberation in rooms which are too "dead" for satisfactory listening;

(f) for Motion Picture Theaters;

(g) to distribute radio or recorded programs in factories, schools, hospitals, hotels, restaurants, recreational buildings, etc., for entertainment, audio instruction, or therapeutic purposes, and also to enhance morale, thus increasing productivity and quality of the product;

(h) to provide paging and announcing in offices, stores, industrial buildings, schools, hotels, hospitals, transportation buildings or in any other building for the purpose of transmitting spoken or recorded announcements or for locating individuals;

(i) to provide a multitude of electro-acoustical facilities in Theaters, Opera Houses, etc., partly for the convenience of the audience, performers and staff, and partly to produce various sound effects;

(j) to provide personal communicating facilities between individuals at separated locations in the same or different buildings;

(k) to provide hearing aids in Auditoria;

(l) to operate electronic organs, chimes, carillons, etc.;

(m) for signalling, i.e., to relay instructions for emergency action or for indicating the beginning and end of work periods.

Some of these listed functions are often combined.

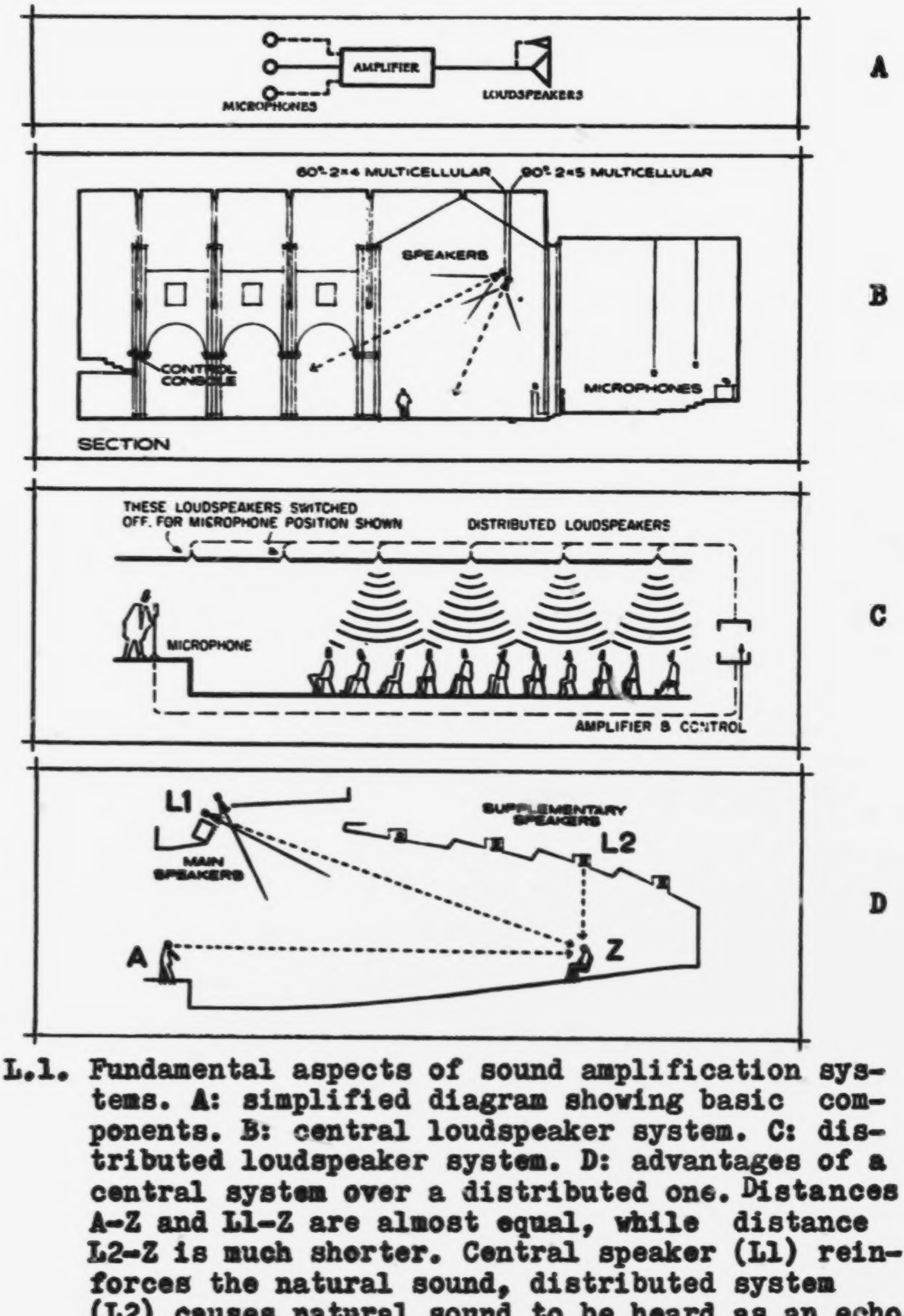
In the remainder of this Section mainly sound amplification systems used to reinforce the sound level in Auditoria will be discussed. It is generally expected that a sound system (a) should provide clear and undistorted sound, i.e., high intelligibility, at reasonable loudness; (b) should be free from disturbing echoes; (c) should create a sufficiently low room reverberation; and (d) the amplified nature of the sound should remain undetected. In fact, the audience should be unaware of the existence of a sound system, and the acoustical excellence of any performance should be attributed to the performers and to the acoustics of the Auditorium (L-7, L-37, L-43).

L.2 System Components

Every single-channel sound amplification system is a hookup of three essential components: microphone, amplifier and loudspeaker.

The microphone, placed near the actual sound source, picks up the sound energy radiated by the source, converts it into electrical energy and feeds it into the amplifier. The amplifier increases the magnitude of the electrical signal and delivers it to the loudspeaker which converts the electrical signal into air-borne sound waves for distribution to the listeners at a requested level (L-3, L-6, L-33, L-35, L-40, L-53). Figure L.1.A is a simplified diagram showing basic components of a single-channel sound amplification system.

A detailed discussion of the system components (microphones, amplifiers and loudspeakers) is beyond the scope of this work (L-1, L-2, L-3, L-6, L-7, L-9, L-15, L-16, L-18, L-20, L-22, L-25, L-26, L-33, L-35, L-37, L-40, L-43, L-52, L-53, GB-38). It must be stressed that a sound system will give satisfactory results only if all components are of the highest quality, if its design is carefully integrated with the architectural and acoustical characteristics of the Audi-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MICROPHONES
AMPLIFIER
LOUDSPEAKERS
B
60° 2×4 MULTICELLULAR
90° 2×5 MULTICELLULAR
SPEAKERS
CONTROL CONSOLE
MICROPHONES
SECTION
C
THESE LOUDSPEAKERS SWITCHED OFF. FOR MICROPHONE POSITION SHOWN
DISTRIBUTED LOUDSPEAKERS
MICROPHONE
AMPLIFIER & CONTROL
D
L1
MAIN SPEAKERS
SUPPLEMENTARY SPEAKERS
L2
A
Z

Figure L.1. Fundamental aspects of sound amplification systems. A: simplified diagram showing basic components. B: central loudspeaker system. C: distributed loudspeaker system. D: advantages of a central system over a distributed one. Distances A-Z and L1-Z are almost equal, while distance L2-Z is much shorter. Central speaker (L1) reinforces the natural sound, distributed system (L2) causes natural sound to be heard as an echo. (Reprinted from Acoustical Designing in Architecture by V.O. Knudsen and C.M. Harris, John Wiley and Sons, New York, 1950; and Progr. Arch., Ag. 1961; Arch. Rec., Dec. 1961).

torium, and if the system is operated by a competent person who has a fundamental understanding of the sound program and of the temperament of the performers (L-3).

L.3 Loudspeaker placing

If the microphones are to be located at the "sending" end of an Auditorium there are available three principal types of loudspeaker systems (L-3, L-7, L-37, L-43, L-53):

(a) centrally located, with a single cluster of loudspeakers over the sound source, as shown in Figure L.1.B;

(b) distributed, using a large number of overhead loudspeakers located throughout the Auditorium, as illustrated in Figure L.1.C;

(c) stereophonic, with two or more clusters of loudspeakers around the proscenium opening or the sound source.

The central system (Figure L.1.B), the most preferred one, gives maximum realism because the amplified sound comes from the same direction as the original sound. This will create the impression of increased loudness and clarity but the audience will identify the sound with the performer, not with the loudspeaker (L-3, L-52).

As a rule, the use of a central loudspeaker system should be preferred, however, there are many situations in which a distributed system (Figure L.1.C) has to be used; for example (L-52, L-53):

(a) in Auditoria with a low ceiling height that is inadequate for the installation of a central system;

(b) where a majority of the listeners would not have adequate line-of-sight on a central loudspeaker;

(c) when sound has to be provided for overflow audiences;

(d) in large halls (Convention Halls, Ballrooms, Terminal Buildings, etc.) where maximum flexibility is required to amplify sound sources in any part of the hall, and where the amplified sound has to override the prevailing high background noise level;

(e) in halls where the possibility exists of dividing the space into several smaller areas.

Although no realism can be expected from a distributed loudspeaker system, it does provide a high degree of intelligibility if the room is not too reverberant.

In the distributed system, several loudspeakers are placed in the ceiling, facing down towards the audience and operated at a relatively low but comfortable sound level; each speaker is placed so that it covers only a specified area.

If amplified sound is supplied through a distributed system to a listener seated at the rear of a very long room, he will receive the amplified sound earlier than the natural sound. If this delay in the arrival of the natural sound is excessive, the sound will appear to come from the loudspeaker resulting in loss of intelligibility and disillusion in listening. This can be overcome if an appropriate time-delay mechanism is introduced in the sound amplification system (L-30, L-43, L-45, L-52, L-53).

The use of a central loudspeaker system is nearly always preferable to the distributed system as is illustrated and explained in Figure L.1.D.

The simultaneous use of both the central and the distributed loudspeaker systems in certain Auditoria is feasible, sometimes quite necessary.

A stereophonic sound system employs two or more microphones adequately spaced in front of the performing area, connected through separate amplifying channels to two or more corresponding loudspeakers spaced in front of the listening area. Such a system will preserve the illusion that sound is coming from the original, unamplified source, because (a) sound will, in fact, approach from loudspeakers above (or below) the original source at intensities proportional to the distance from the source to the microphone, and (b) the ear locates sound sources in the horizontal plane but not in the vertical plane (GB-38).

A stereophonic sound system, used mostly on large stages where the sound originates from moving sources or grouped voices and instruments, will preserve the audio illusion in the spatial distribution of the sound sources. It will create a remarkable increase in the realism of sound and listening pleasure (L-22, L-32, L-37, L-41, L-43, L-47, L-48, L-49, L-53, L-54).

The use of a stereophonic sound system in Auditoria will require particular attention in obtaining the optimum layout of equipment and in the inclusion of the increased number of system components in the overall design (L-3).

If the microphones are distributed in an Auditorium (Parliamentary Halls, Conference Halls, etc.), the loudspeaker layout will require an individual solution in every case (L-37).

In placing the loudspeakers, in general, it must be remembered that (a) every listener in the room must have line-of-sight on that particular loudspeaker with which it is planned to supply him with amplified sound, (b) a loudspeaker cluster (particularly the central type) will require a great deal of space, and (c) concealed loudspeakers have to be hidden behind a sound transparent grille which should not contain large scale elements (L-53).

Loudspeakers should always radiate their sound energy on the sound absorbing audience with no (or minimum) sound energy radiated on sound reflecting surfaces. This is particularly important in Auditoria with excessive R.T.

Various types of loudspeakers can be used for both the central and distributed systems. In certain cases "line" or "column" loudspeakers are preferable to the conventional radial or multicellular horns. Column loudspeakers concentrate most of the sound into a beam which has a wide angular spread in the horizontal plane and a narrow angular spread in the vertical plane, shown in Figures L.2 and L.3 (L-7, L-37, L-39).

Even though the selection of the central loudspeaker cluster is in the hands of the electrical engineer, the integration of the space-consuming central loudspeaker system with the architectural concept is always a serious aesthetic problem unless it is tackled by the architect from the outset of the design.

Particular attention must be paid to the locations of microphones relative to the loudspeakers in both central and distributed systems, in order to avoid the familiar feedback, i.e., squealing or howling. This phenomenon, typical of a poorly designed sound system, usually occurs (a) if the sound radiated from the loudspeaker is picked up by the microphone, (b) whenever reflective surfaces of the room are so located as to concentrate reflected sound on the microphone, and (c) in highly reverberant rooms.

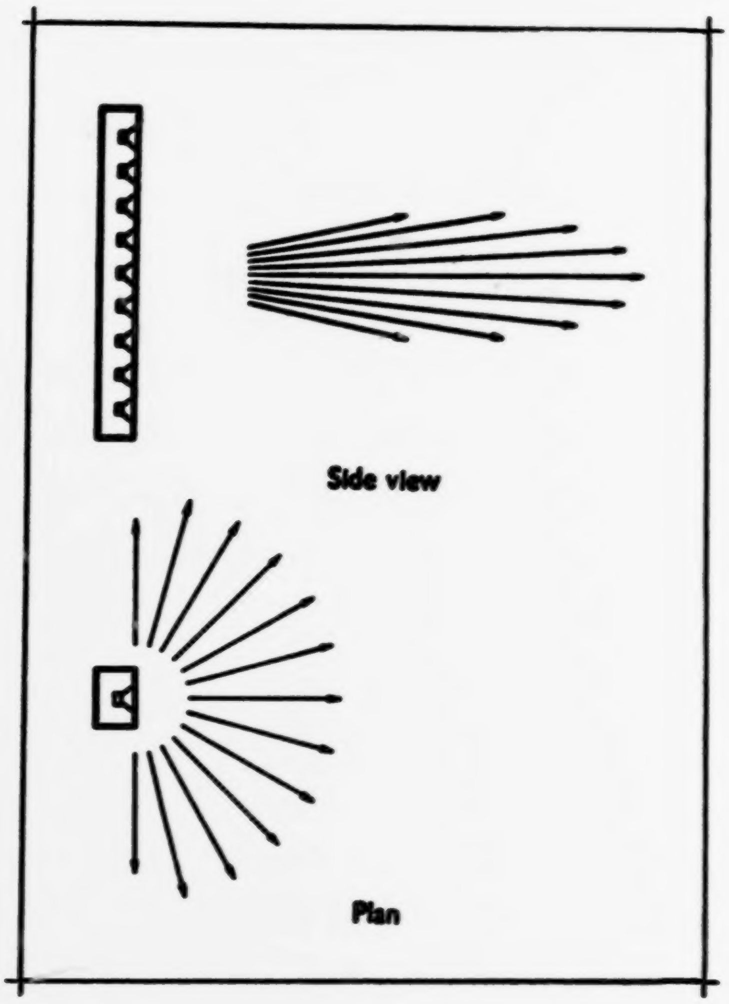

Figure L.2.

Diagrammatic illustration of a "column" loudspeaker, showing its wide angular spread in the horizontal plane and its narrow angular spread in the vertical plane. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

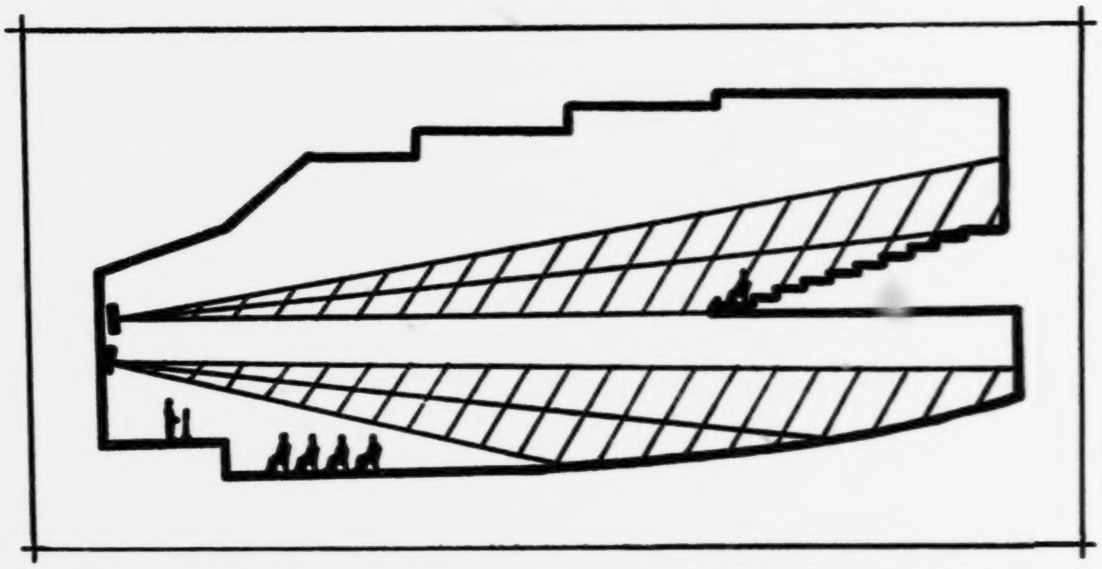

Figure L.3. Longitudinal section of an Auditorium with central loudspeaker system; two "column" loudspeakers are used with narrow angular spreads in the vertical plane. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

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(See list of abbreviations on page 1)

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PART III.
NOISE CONTROL

Section M. General Principles of Noise Control

M.1 Effect of noise on people

M.2 Measurement of noise. Addition of noise levels

M.3 Noise sources

  M.3.1 Noise sources indoors
  M.3.2 Outdoor noises

M.4 Air-borne sound, structure-borne (impact)sound

M.5 Transmission of noise in buildings

  M.5.1 Transmission of air-borne noise
  M.5.2 Transmission of structure-borne noise and vibration

M.6 Methods of noise control

  M.6.1 Suppression of noise at the source
  M.6.2 Noise control by means of town planning
  M.6.3 Noise control by means of site planning and landscaping
  M.6.4 Noise control by means of architectural design
  M.6.5 Noise control by means of structural design
  M.6.6 Noise control by means of mechanical design
  M.6.7 Noise control by means of organization
  M.6.8 Noise reduction by means of sound absorptive treatment
  M.6.9 Noise control by means of sound insulating building construction
  M.6.10 Noise control with masking noise

References

In the introductory pages of this study it was noted that buildings today exist in a relatively noisy environment as a result of the remarkable shift in building technology from traditional (heavy and thick) structure to contemporary (lightweight, thin, and prefabricated) building construction, the extraordinary increase in noise sources, and the architect's preference for undivided interior spaces (M-2, M-6, M-8, M-17, M-20, M-81, M-82, M-122).

The elimination or reasonable reduction of interior and exterior noises in buildings, i.e., the provision for the desired quiet environment, is the purpose of noise control, and the subject of this and subsequent Sections. Freedom from noise is one of the most valuable qualities that a contemporary building can possess (M-6).

M.1 Effect of noise on people

All sounds regarded as distracting, annoying or harmful to everyday life (work, rest, study, entertainment, etc.) are considered as noises; as a standard definition, any sound deemed undesirable by the recipient is regarded as noise (GB-73). Thus speech or music will also be regarded as noise when their perception is undesired by the recipient (M-6, M-13, M-17, M-20, M-27, M-83, M-84, M-122). Whether or not a sound is undesired by a person will naturally depend on the loudness of the sound, and also on subjective aspects; such as, origin of sound, the recipient's momentary state of mind, his state of nerves, etc. (M-88, M-89, M-103). Music may sound lovely if produced by one's own record player but it can be quite irritating if it comes from the neighbor's radio or television set (M-116, M-122, M-141). Noise created by oneself tends to be ignored if it constitutes a natural accompaniment to work, such as the noise of a typewriter, of a working machine, etc. (M-11). Quite often noises originating from a nearby railway station or from distant airflights are not objectionable (provided that their perception is not unexpected) because their origin is considered as something necessary and natural (GB-52). As a rule, noises of mechanical or electrical origin (caused by fans, transformers, motors, pumps, vacuum cleaners, washing machines, etc.) are always more annoying than noises of natural origin (wind, rain, waterfall, etc.). High frequency noises are more disturbing than low frequency noises (GB-52).

The effects of noises, ranging from distracting to serious, are well known. Even a faint noise can interfere with listening to speech or music, causing a masking effect (subsection C.8) and elevating the threshold of audibility (M-11, M-14, M-16, M-22, M-26, M-44, GB-21). Moderately loud noises may produce nervousness, indisposition, auditory fatigue, indigestion and circulatory troubles. Very loud noises may induce a serious deterioration in a person's general state of health ; if long endured, temporary or permanent loss of hearing can result (M-6, M-11, M-56, M-84, M-102, M-113).

The detrimental effect of noise on working efficiency and production has been numerically proven in several fields of industry (M-6, M-84, M-119).

M.2 Measurement of noise. Addition of noise levels

Noise can be measured in different ways (M-3, M-16, M-21, M-45, M-46, M-47, M-70, M-86, M-96, M-97, M-100, M-125). The sound pressure level and sound level of noise is measured by means of a sound pressure level meter in terms of decibels above 0.0002 microbar (subsection C.3).

The subjective loudness of a sound, however, varies not only with the sound pressure level but also with the frequency of the sound. The way the loudness of a sound varies with frequency will depend on the sound pressure level of the sound; in addition, low frequency sounds seem less loud than high frequency sounds which have the same sound pressure level (M-26). Allowance has been made for this effect for pure tones by incorporating so called "weighting networks" in an instrument that measures sound pressure levels; such an instrument is called a sound level meter (M-21, M-85, M-96, M-125, M-135).

In order to obtain a high degree of uniformity among sound level meters, they provide three alternate frequency-response characteristics. The three responses are obtained by three weighting networks, designated A, B, and C, also referred to as "40 dB", "70 dB", and "flat", respectively, shown on Figure M.1. These responses selectively discriminate against low and high frequencies according to the equal-loudness level curves in Figure C.1, and approximating, to a certain extent, the frequency response of the human ear. If A-weighting is used, for measuring noise levels below 55 dB, it will indicate the "A-weighted sound level", and the measurement should be labelled "dB-A". Similarly for B-weighting, used for noises between 55 dB and 85 dB. C-weighting is used for noises above 85 dB. When noises are measured on a sound level meter with the frequency response weighting selected according to the level of the measured noise, the reading obtained is the sound level. Readings obtained with the "flat" (or "C") frequency response are sound pressure levels. It is essential to record the weighting position with the observed level (M-21).

When the frequency characteristic of a noise has to be investigated, the sound level meter is used with a spectrum analyzer. The analyzer has a set of filters allowing a certain band of frequencies only to pass through a circuit; only those frequencies allowed through will be measured by the sound level meter. The usual type of analyzer, called an octave-band ana-

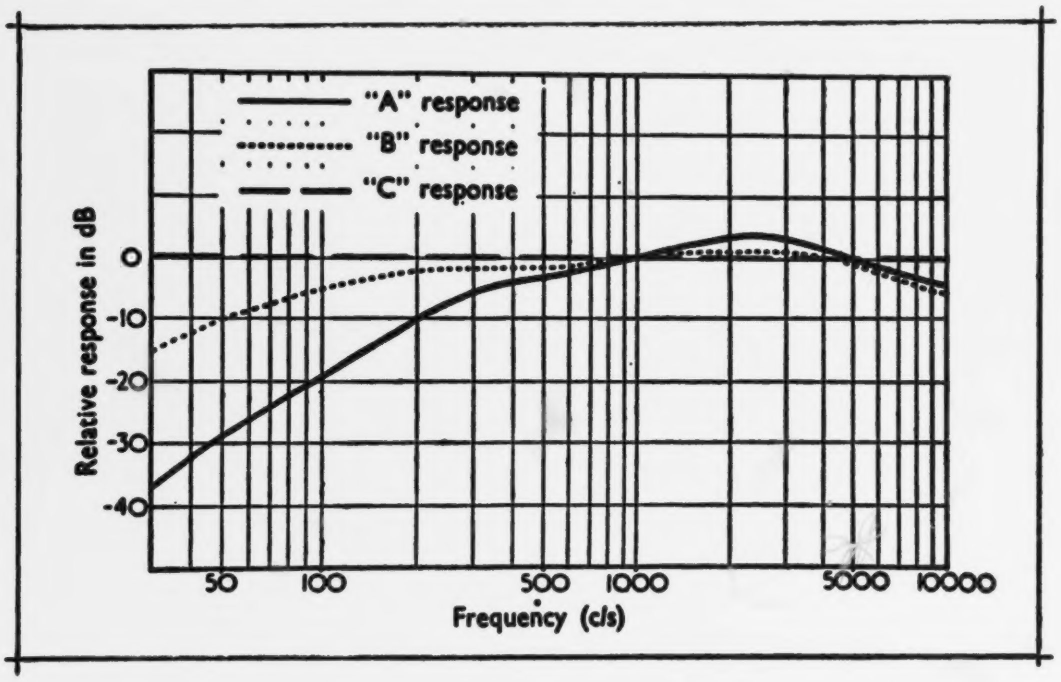


Figure M.1. "A", "B", and "C" responses of a sound level meter. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

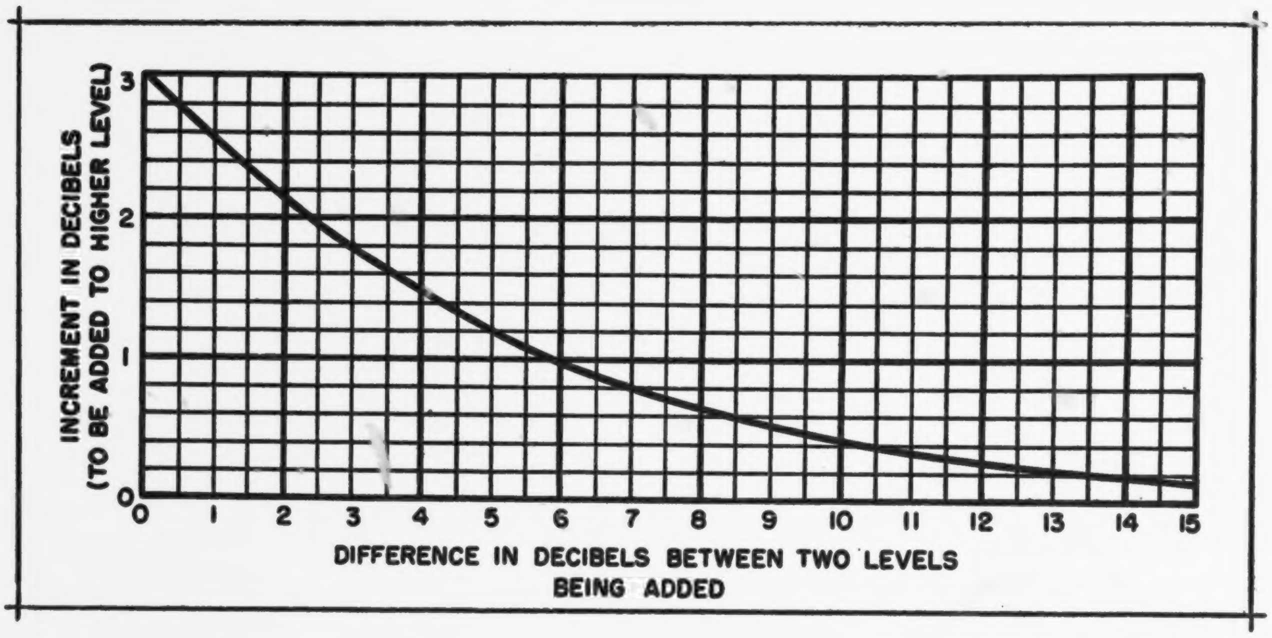


Figure M.2. Chart for combining noise levels. (Reprinted from Handbook of Noise Measurement by A.P.G. Peterson and E.E. Gross, General Radio Company, West Concord, Mass., 1960).

lyzer, is divided into several bands of one octave each. A noise is properly specified when one average reading is given for each octave band on the appropriate weighting network (M-26).

Sound levels for typical noise sources measured with a sound level meter are listed in Table M.1 (M-6, M-21, M-28, M-29, M-30, M-49, M-74, M-75, N-10).

Table M.1. Typical overall noise levels, expressed in decibels, measured at a given distance from the noise source. (Levels below 85 dB are weighted).

Noise source	noise level, dB, re 0.0002 microbar
Ticking of watch	20
Quiet garden	30
Average residential environment	43
Light traffic (100')	45
Average private business Office	50
Acounting Office	65
Average traffic (100')	67
Boeing 707-120 jet at touch-down (3300')	70
Automobile (20')	74
Heavy traffic (25' to 50')	75
Average light truck in city (20')	77
Lathes (3')	80
Cotton spinning machines (3')	85
Inside sedan in city traffic	86
10 HP outboard (50')	88
Boeing 707-120 jet at take off (3300')	90
Inside motor bus	91
Train whistles (500')	92
Average heavy truck (20')	93

(Table M.1 cont'd.)

Noise source	noise level, dB, re 0.0002 microbar
Subway train (20')	95
Sewing machines (3')	96
Looms (3')	97
Riveting gun (3')	100
Wood saw (3')	100
Inside DC-6 airliner	105
Chipping hammer (3')	108
Automatic punch press (3')	112
Car horn (3')	114
Pneumatic chipper (5')	123
Large pneumatic riveter (4')	128
Hydraulic press (3')	129
F 84 jet at take-off (80' from tail)	132
50 HP siren (100')	138

If the combined noise level of two or more different noise sources has to be predicted, the resultant noise level will not be the sum of the individual levels. The diagram given in Figure M.2 can be used, with reasonable approximation, for combining two noise levels, but the diagram can also be used successively to combine any number of noise levels. If the sound pressure levels S_1 and S_2 of two noise sources have to be added and if S_2 is greater than S_1, then, the total noise level in decibels is equal to $S_2 + N$, where N is the increment to be determined from Figure M.2, corresponding to the difference between the two sound pressure levels being added. It will be seen that when the sound pressure levels of two noise sources are equal, the difference between them equals zero, and the resultant noise level is 3 dB higher than the level of either sound source (M-6, M-21). If several noise sources, all having the same sound pressure level, have to be added, they will have a total sound pressure level which is 10 $\log_{10} q$ decibels above the sound pressure level of one of the noise sources, where q is the number of the noise sources (M-11).

Various methods are known and instruments used for the measurement of vibration; their discussion, however, falls beyond the bounds of this study (M-16, M-22, M-53, GB-34).

M.3 Noise sources

The main noise sources of significance in noise control may be classified in two groups (M-4, M-6, M-11, M-17, M-18, M-37, M-40, M-122, S-30, S-38, S-40, S-43, GB-52):

(a) noise sources indoors, originating from people, household equipment, or machinery within the building. Partition walls, floor constructions, doors and windows inside the building must provide adequate protection against these noises;

(b) outdoor noises, originating from traffic, transportation, industry, and from sports activity. Exterior walls and top floors (roofs) must provide the required protection against outdoor noises.

Even though these noise sources may occur indoors or outdoors, in subsequent discussions their effect will be considered from the point of view of the recipients who are assumed to be indoors (M-18).

If the noise originates in a room, this will be called the source room, and the room in which the recipient is located will be termed the receiving room (M-18).

M.3.1 Noise sources indoors

The most common noise sources produced by people (particularly in Apartment Buildings) are: radio or television sound coming from adjacent occupancies, banging of doors, loud conversation, traffic on staircase, people moving, children playing, babies crying, etc. (M-11).

Building noises produced by various household equipment, machinery, etc.,represent more serious sources of interference. These articles of equipment and machinery are being increasingly replaced by contemporary units of greater output, higher speed, and consequently of increased noise.

Extremely high noise levels are produced in several industrial buildings due to various manufacturing or production processes.

Table M.2 presents average sound levels of characteristic noises produced in buildings (M-6, GB-52).

Table M.2. Average noise levels of typical noises, expressed in decibels, produced in buildings

Noise source	noise level, dB, re 0.0002 microbar
Large orchestra in a Concert Hall	
peak level	110 (C)
average level	90 (C)
minimum level	50 (C)
Radio music in a noisy Living Room	
peak level	83 (C)
average level	70 (C)
minimum level	58 (C)
Radio music in a quiet Living Room	
peak level	78 (C)
average level	65 (C)
minimum level	47 (C)
Speech	
loud speech (3'-6" distance)	80 (C)
raised voice (3'-6" distance)	74 (C)
normal speech (3'-6" distance)	68 (C)
low-toned conversation (3'-6" distance)	60 (C)

(Table M.2 cont'd.)

Noise source	noise level, dB, re 0.0002 microbar
Average noises in Offices	
3 persons	55 (C)
10 persons	60 (C)
50 persons	65 (C)
telephone ring (6'-6" distance)	75 (A)
typewriter, standard (6'-6" distance)	70 (A)
typewriter, noiseless (6'-6" distance)	60 (A)
Office with tabulating machines	78 (B)
Boiler Shop	
peak level	127 (C)
average level	114 (C)
Weaving Room	104 (C)
Shoe Factory	104 (C)
Woodworking Shop	108 (C)

Measured noise levels, as given for instance in Table M.2, provide us with important clues whenever noises have to be reduced in the receiving room by the use of appropriate sound insulating enclosures.

The noise level at any position in a room is made up of two parts: (a) sound received directly from the source, and (b) the reflected or reverberant sound reaching the position under consideration after repeated reflections from the boundary surfaces of the room. This is illustrated in Figure M.3. Around the noise source the direct sound predominates, gradually falling off with increasing distance from the source (M-18). Further away from the noise source the reverberant sound will prevail, being close to equal strength throughout the room (provided that the noise source is non-directional), as illustrated in Figure M.4 (M-18).

If measurements of noise levels are required in a room, it will be necessary to ascertain whether it is the direct or reverberant noise level which is being measured (GB-43). In the

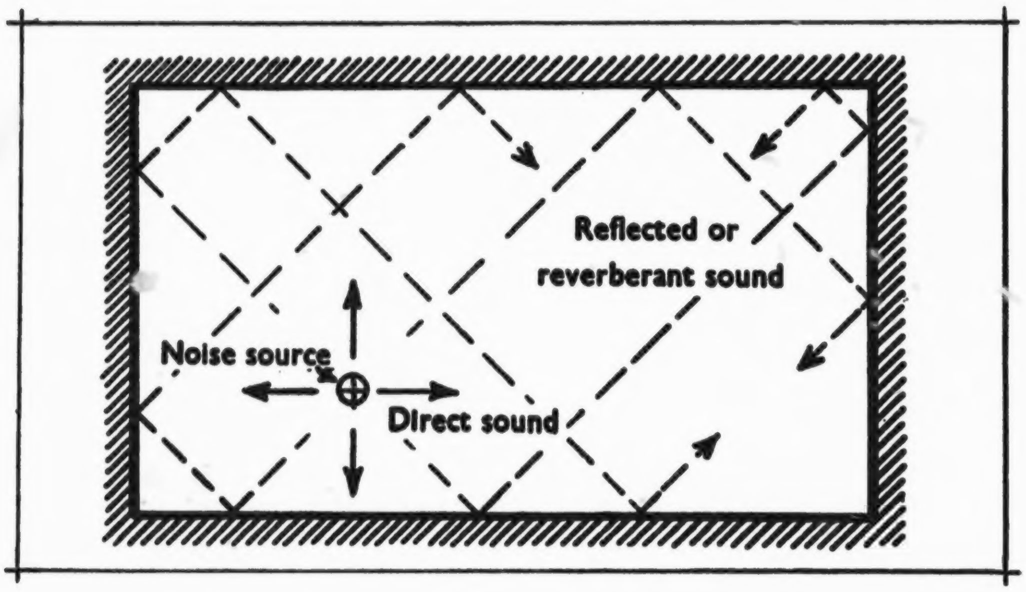

Reflected or
reverberant sound
Noise source
Direct sound

Figure M.3. Direct and reverberant sound in a room. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

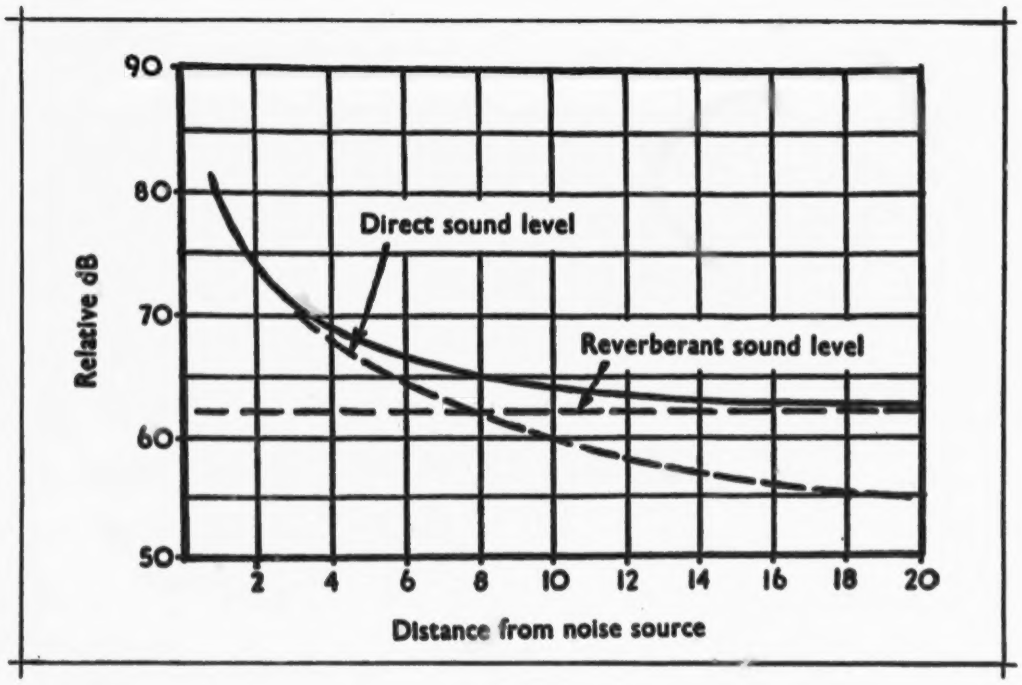


Figure M.4. Decrease in intensity of sound with distance from source. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

design of sound insulating enclosures it will be more important to know the reverberant sound level than the direct sound level because it is the reverberant sound that hits the room enclosures,and so is more likely to be transmitted to other rooms of the building. If a room noise that has been found to be excessive for the people in the same room has to be reduced, then both the direct and reverberant sounds are of interest (M-18); this will be considered in paragraph M.6.8.

M.3.2 Outdoor noises

Outdoor noises are harmful contributors to noisy buildings. The most annoying noises of this kind are produced by vehicular, railroad and air traffic, and transportation. A preliminary noise survey always should be made at sites chosen for buildings in which quietness is essential (Churches, Studios, Hospitals, Schools, etc.) in order to make some preliminary allowance for the required noise control measures necessitated by outdoor noises (M-18).

The advent of jet and supersonic aircrafts, for both civilian and military purposes, has introduced the most complex types of noise control problems that now confront acoustical experts (M-17, M-23, M-76, M-88, M-95, M-110, M-123, M-127, M-128, M-139, N-81, R-25, R-39). Aircraft noises, particularly during ground run-up and take-off operations, affect not only living and working conditions around the airport,but also large areas of densely populated districts, regrettably located along air routes, are subjected to objectionable noise levels (M-128). Noise levels of aircrafts under specified conditions are given in Table M.1.

The noise level created by vehicular traffic will depend on the type of vehicles, their number, speed and the frequency of their occurence. Noise levels of vehicular traffic are given in Table M.1.

The reduction of the intensity of outdoor noises with distance is governed by the inverse square law; a drop of 6 dB will be noticeable every time the distance between the source and recipient is doubled (subsection C.9). In addition, there is attenuation due to molecular absorption, mainly at frequencies above 1000 cps (M-18).

Besides molecular absorption, other weather factors, such as, wind and temperature gradients, snow, clouds, and fog will also affect the propagation of noise in the open air (M-18).

An obstruction (wall, embankment, building, etc.) will contribute to the attenuation of outdoor noises only if the dimension of the obstruction is comparable with the wavelength of the noise; the attenuation provided by obstructions is, however, rather limited (M-18, M-25).

M.4 Air-borne sound, structure-borne (impact) sound

Sound can be produced (a) in the air, such as the human voice or musical sounds, (b) by impacts, such as the dropping of objects on a floor, the slamming of doors, (c) by machinery vibration, and (d) by the flow of fluids, such as air in ducts (M-26). The sound thus generated at the source will travel through various paths in a building (M-4, M-6, M-11, M-17, M-18, M-24, M-26).

If a sound is transmitted through the air only, it is called air-borne sound. A speaking person, a singer, the violin, the trumpet, etc., generate air-borne sounds. This is illustrated in Figure M.5 (GB-52).

If a sound source radiates its energy not only through the air but also simultaneously sets into vibration solid parts of the building structure, it is termed structure-borne sound, or impact sound. The sound of a cello, double bass, and footstep noises represent typical structure-borne sounds. This is illustrated in Figure M.6 (GB-52).

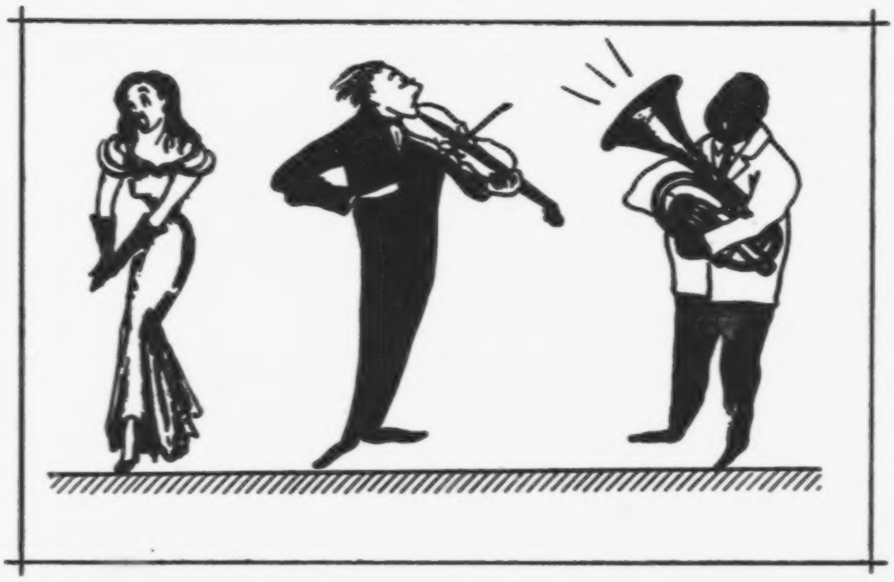


Figure M.5. Sound sources producing air-borne sounds. (Reprinted from Raum- und Bauakustik, Lärmabwehr by W. Furrer, Birkhäuser Verlag, Basel 1961).

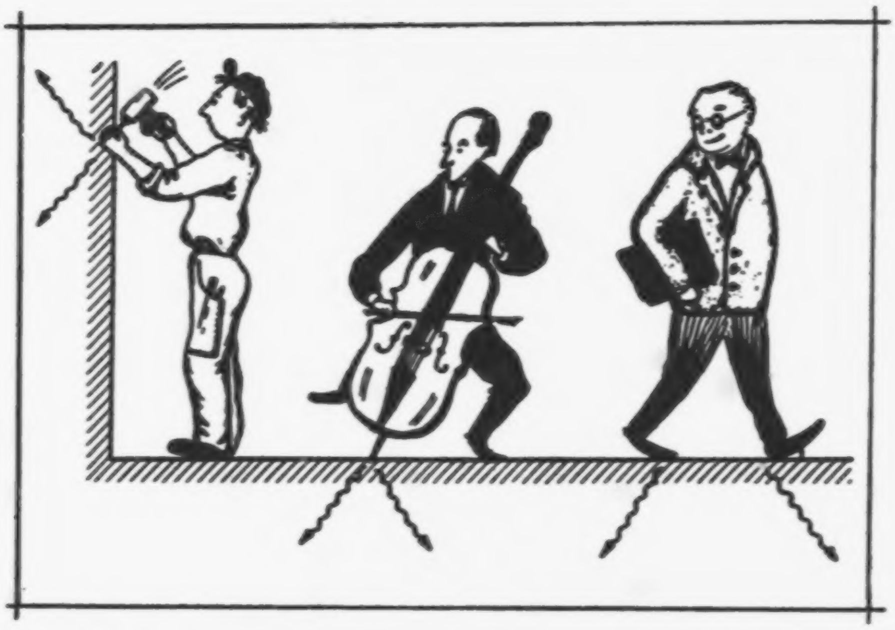


Figure M.6. Sound sources producing structure-borne or impact sounds. (Reprinted from Raum- und Bauakustik, Lärmabwehr by W. Furrer, Birkhäuser Verlag, Basel, 1961).

Similar to air-borne sounds and structure-borne sounds, air-borne noises are to be distinguished from structure-borne noises. From the point of view of a recipient, structure-borne noises cannot be separated from air-borne noises. Structure-borne noises transmitted through the structure will be re-radiated from certain building elements, such as walls, slabs, panels, suspended ceilings, furred-out plasters, building boards, etc., and will eventually reach the recipient as an air-borne noise.

M.5 Transmission of noise in buildings

The transmission of air-borne sound differs considerably from that of structure-borne sound (M-6, M-18, GB-52).

Air-borne sounds are attenuated considerably by air absorption and also by intervening enclosures (walls, floors, etc.), so that their effect is confined mostly to areas near their origin.

Structure-borne sounds, by setting solid parts of the building structure into vibration, virtually multiply the area of the sound radiating surface, thereby increasing the radiated sound pressure. Sometimes this growth of the area of the sound radiating surface is useful, even desirable, e.g., with musical instruments, such as, cello, double bass, piano, etc. (subsection H.3). In many cases, however, this phenomenon is very harmful. A vibrating heating pipe or water pipe alone would radiate a very small amount of air-borne noise, due to its limited surface; however, if these pipes, as usually is the case, are rigidly anchored to a wall or to a floor slab, additional large surfaces will be set into vibration, greatly increasing the radiated noise and transmitting the vibration over surprisingly long distances.

The means of suppression of air-borne noises (air-borne sound insulation) are different from those of insulating structure-borne noises (structure-borne sound insulation). A boundary that provides good protection against one type of noise may be a poor insulator against the other. It is, therefore, important to find out whether the noise that has to be combatted originates from air-borne sounds or from structure-borne sounds (M-6, M-11, M-52, M-53).

M.5.1 Transmission of air-borne noise

Air-borne noises originating in the source room can be transmitted to the receiving room in the following ways (M-6, M-18, M-52, GB-29, GB-52):

(A) Along continuous air paths through openings; such as, open doors and windows; ventilating ducts and ventilating grilles; shafts, crawl spaces; gaps and cracks around doors, pipes, conduits, electrical fixtures, and built in elements, etc.

(B) By means of forced vibrations set up in the boundaries (walls, floor, ceiling) of the source room and transmitted to the boundaries of the receiving room; these forced vibrations will then be re-radiated in the receiving room. If source room and receiving room have a common boundary (partition wall or floor), the re-radiated sound might be particularly noticeable unless the boundary in question offers sufficient resistance to flexural vibrations (i.e., it has adequate mass).

M.5.2 Transmission of structure-borne noise and vibration

Since structure-borne noises and vibrations are readily transmitted with little attenuation and over great distances in a building, structure-borne noises and vibrations should be suppressed right at their source, where possible, or as close as possible to it. This will be accomplished (M-6, M-18, M-53, M-80, M-91):

(a) by the use of adequately resilient flooring (carpeting, rubber tile, cork tile, etc.) to reduce impact transmissions to the floor;

(b) by the use of a segment of flexible (metallic, rubber, or plastic) hose or canvas in pipes, ducts, etc., to prevent the transmission of vibrations along them;

(c) by the use of flexible mountings, anti-vibration pads, floating floors, etc., to prevent the transmission of vibration and shock from various machinery or exterior sources into nearby precision machines, delicate equipment or into the building itself (discussed in Section N).

M.6 Methods of noise control

Various approaches can be followed to achieve an effective and economical elimination or reduction of noises in buildings (M-1, M-2, M-5, M-8, M-13, M-20, M-22, M-33, M-39, M-48, M-58, N-18, N-38). It is becoming strikingly obvious that the fight against the ever increasing number of harmful noises will lead to satisfactory results only if all those participating in the design of buildings will take their share of achieving the common goal (M-99).

Noise control can also be accomplished by means other than design, e.g., through certain modifications of the source or transmission paths, or by adequate reorganization of the entire noisy area. These measures are in the hands of the manufacturers, office management, etc.

The various methods of noise control will be described briefly in subsequent paragraphs.

M.6.1 Suppression of noise at the source

The most economical noise control measure is to suppress the noise right at the source by using quietly working machines and equipment, and also by adopting manufacturing processes or working methods which will cause as low a noise level as possible (M-16, N-49, N-149). For example, a change from riveting to welding, or from hammering to the use of hydraulic presses, will eliminate serious noises.

Proper maintenance of machinery is always a good noise control practice because loose housings, guards and vibrating parts of a machine are always noise sources. Sometimes very noisy machines can be enclosed in specially designed housings if they cannot be quieted directly (M-78). An enclosure around the offending unit should (a) have weight, (b) be impermeable to air, and (c) be lined with sound absorbing material (M-79, N-49, N-149).

In the design and manufacturing of competitive typewriters, vacuum cleaners, motors, fans, compressors, boilers, etc., the achievement of a relatively noiseless operation is one of the objectives (M-11).

Footstep noises are easy to reduce at the source by the use of soft floor finishes; such as,carpet, cork, rubber tile, vinyl tile, etc. (M-11).

M.6.2 Noise control by means of town planning

The following are the principal types of community noise: (a) transportation noise, (b) industrial noise, and (c) noise produced by people (M-6, M-11, M-88). Noises produced by these sources can be reduced by suitable layout of traffic arteries and by careful segregation of residential districts from highways, main streets, railways, and airports (M-37, M-59, M-61, M-63, R-20, S-38).

Highways should be routed around, not through, areas zoned for buildings requiring quiet surroundings (Churches, Hospitals, Schools, Residential Buildings, etc.). Traffic arteries and railway tracks passing through quiet-requiring areas should be shielded by means of hills, embankments or cuttings along the edges of the route and should be located a proper distance from populated areas. They should be planned to permit their coordination with new residential areas as need arises (M-134). Trains should enter large metropolitan centres by underground routes. Residential streets should be protected from the noise of traffic feeding the houses (M-6, M-11, M-139).

Contemporary town and community planning with noise abatement in mind(and its implementation through strictly enforced by-laws and zoning regulations) will protect (a) the residents from the intrusion of noise on their privacy, (b) the community against a drop in property value (and hence tax revenue), and (c) the noise producer (manufacturer, operator of a noisy process) from lawsuits and ensuing expenditures for noise control (M-88, R-20).

Figure M.7 shows recommended distances between various industries and residential areas to prevent noise penetration and air pollution (M-139, R-4, R-25).

M.6.3 Noise control by means of site planning and landscaping

Experience shows that once an outdoor noise in a certain area is in existence, it will be difficult to remedy this complaint and to eliminate it from that area. It is, therefore, essential that buildings requiring quiet sonic environment (Schools, Hospitals, Churches, etc.) should be located on

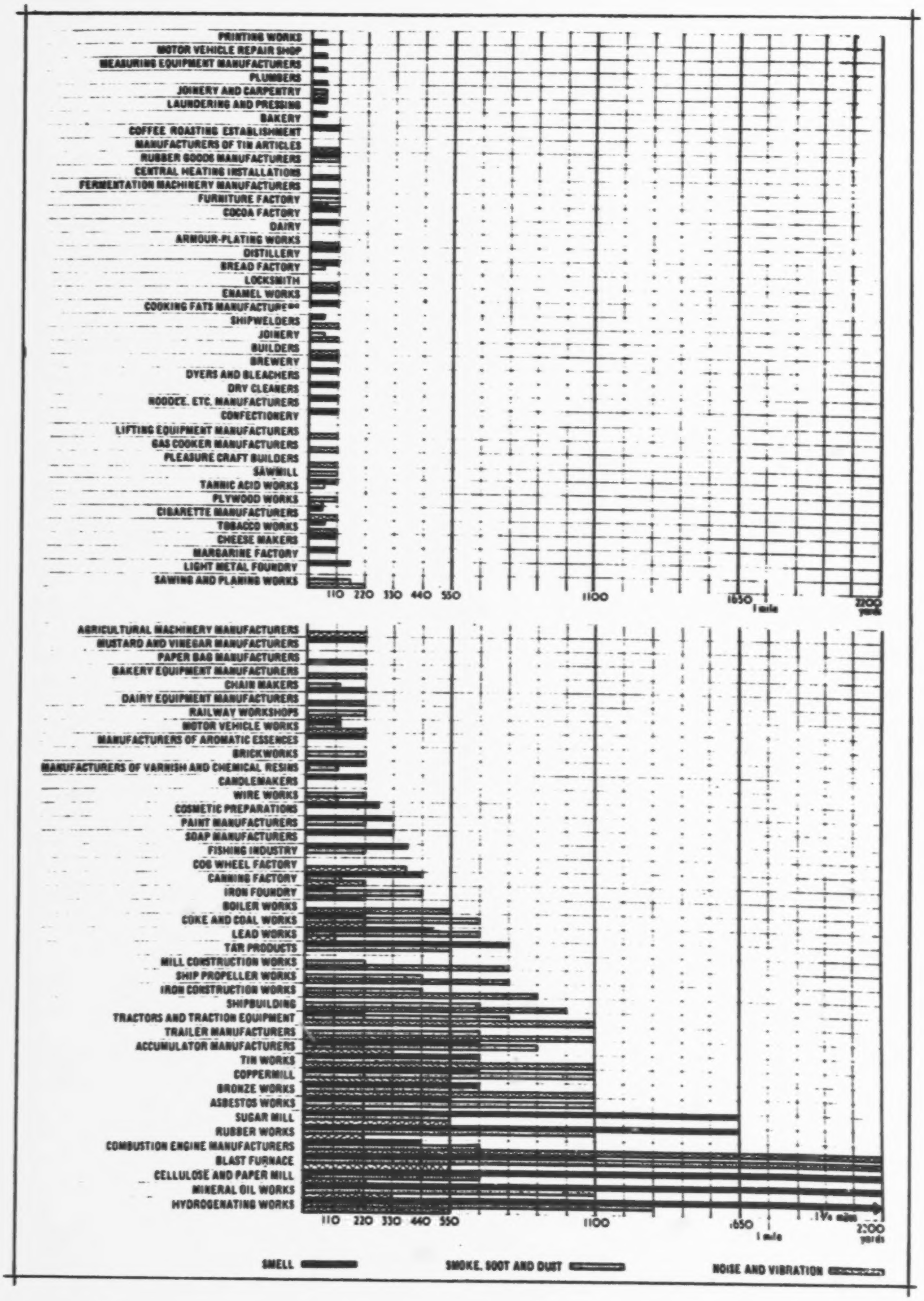


Figure M.7. Chart showing recommended distances between various industries and residential areas to prevent noise penetration and air pollution. (Reprinted from Archs.' J., 13 Feb. 1963).

quiet sites, far away from highways, industrial areas, airports, etc. Under given noise conditions within an area, adequate site planning, grading and landscaping of the site can positively contribute to noise attenuation (M-6, M-105, S-30, S-57).

Linear blocks of buildings should be built with their ends to traffic routes, i.e., the building should stand at right angles to the street (M-6, M-139).

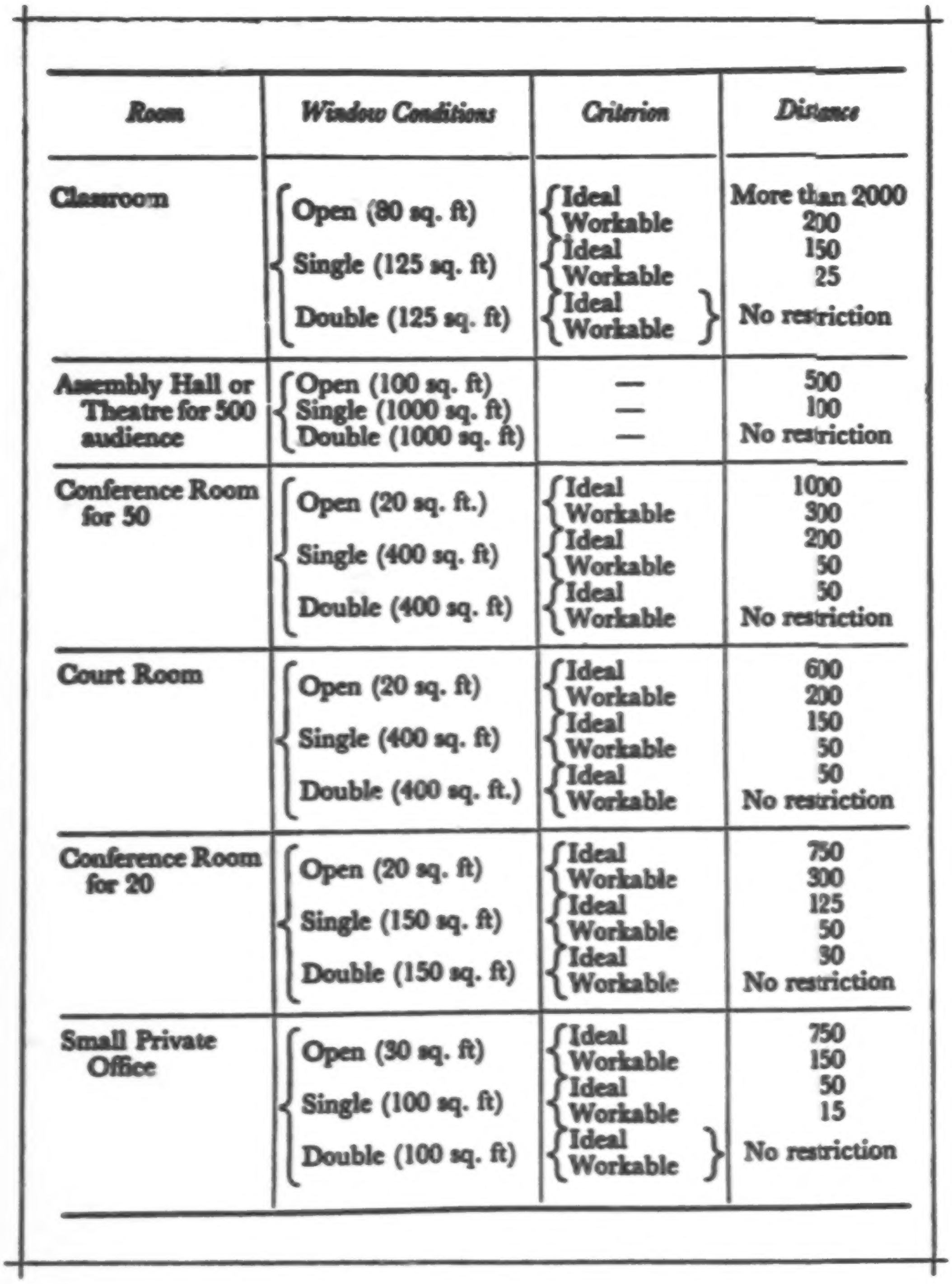
It is always advisable, where possible, to set back a building from the street line in order to make use of the noise-reducing effect of the increased distance between street line and building line (M-6, M-11, M-139).

Buildings not particularly susceptible to noises can be used as noise baffles and can be placed between noise sources and areas requiring quiet (M-6, M-11).

The noise level at the windows of upper floors of high buildings, originating from street noise, is always less than that of the lower floors (M-6, M-18).

Table M.3 lists recommended horizontal distances between a road carrying continuous heavy traffic and rooms of different occupancies facing the road; it is assumed that (a) there is no obstruction between the road and the building containing the room, (b) single windows have 32 oz glazing and are tightly closed, (c) double windows consist of two fully sealed leaves each of 32 oz glazing,and separated by a 4" air space with absorbent in the reveals, and (d) no person in the room is close to the window (M-105).

Table M.3. Recommended horizontal distances (in ft) between a road carrying heavy traffic and rooms of different occupancies facing the road. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).



Room	*Window Conditions*	*Criterion*	*Distance*
Classroom	Open (80 sq. ft)	Ideal	More than 2000
		Workable	200
	Single (125 sq. ft)	Ideal	150
		Workable	25
	Double (125 sq. ft)	Ideal	No restriction
		Workable	
Assembly Hall or Theatre for 500 audience	Open (100 sq. ft)	—	500
	Single (1000 sq. ft)	—	100
	Double (1000 sq. ft)	—	No restriction
Conference Room for 50	Open (20 sq. ft.)	Ideal	1000
		Workable	300
	Single (400 sq. ft)	Ideal	200
		Workable	50
	Double (400 sq. ft)	Ideal	50
		Workable	No restriction
Court Room	Open (20 sq. ft)	Ideal	600
		Workable	200
	Single (400 sq. ft)	Ideal	150
		Workable	50
	Double (400 sq. ft.)	Ideal	50
		Workable	No restriction
Conference Room for 20	Open (20 sq. ft)	Ideal	750
		Workable	300
	Single (150 sq. ft)	Ideal	125
		Workable	50
	Double (150 sq. ft)	Ideal	30
		Workable	No restriction
Small Private Office	Open (30 sq. ft)	Ideal	750
		Workable	150
	Single (100 sq. ft)	Ideal	50
		Workable	15
	Double (100 sq. ft)	Ideal	No restriction
		Workable	

M.6.4 Noise control by means of architectural design

Good architectural planning with attention paid to sound control requirements is the most logical and also a most important approach to effective and economical noise control of buildings (M-6, M-11, M-19, M-32, M-115, M-117, M-118, M-129).

Rooms from which noise is expected, and which can therefore tolerate noise (a) should be isolated from sections of a building that can least tolerate noise, or (b) should be located on those parts of the site which will probably be exposed to other (interior or exterior) noises. Conversely, rooms requiring quiet should be located on the quiet part of the site or side of the building (GB-43).

Rooms (or buildings) not particularly susceptible to noise can be located so that they act as screens or baffles between noisy and quiet areas (GB-43).

In the architectural design of Residential Buildings the rooms should be grouped into quiet quarters and noisy quarters. A quiet quarter includes the habitable rooms, in the first place, the Bedrooms and Study, and in the second place, the Living Room. A noisy quarter contains the Kitchen, Bathroom, Utility Room, staircase, elevator shaft, Boiler Room, Fan Room, etc. In a Residential Building that intends to be soundproof, the following general design rules should be observed (M-6, M-122, S-30, S-41, GB-29, GB-43, GB-52):

(a) quiet and noisy quarters should be concentrated and separated from each other horizontally and vertically by means of adequate sound insulating enclosures (discussed in Section N), or by rooms not particularly susceptible to noises; such as, Entry, Corridor, Lobby, cupboards, closets, staircase, etc.;

(b) a Living Room in one apartment should not be adjacent to a Bedroom in another apartment. Bedrooms in a pair of dwelling units should be adjacent to each other;

(c) Bedrooms should be located in a relatively quiet part of the building and should not overlook traffic lines or driveways;

(d) a Bathroom should be efficiently separated from a Living Room;

(e) the staircase should not be adjacent to Bedrooms;

(f) the separation between quiet quarters and noisy quarters should always fall within the same dwelling unit.

A design that disregards the above recommendations and yet intends to produce a soundproof building will have to use particular sound insulating (and hence expensive) walls and floors.

Figure M.8 shows the floor plan of an ideally-zoned Family House. Admittedly built with an unusual amount of ground coverage and expense, yet it clearly illustrates the required attributes of an acoustically ideal home.

Figure M.9 illustrates another Family House with outstanding acoustical privacy.

Figure M.10 presents typical floor plans of sound proof Apartment Houses in Stockholm-Högdalen and in Basel, incorporating most of the required features listed above.

The patio house and court-garden house provide a higher degree of acoustical privacy compared to the single-family detached house (M-25). This is illustrated in Figure M.11.

M.6.5 Noise control by means of structural design

Sensible structural design often entails noise control requirements (M-115); a few examples are given below to substantiate this statement.

Since the sound insulation of a floor will depend primarily on the thickness of the structural slab, bearing capacity cannot be regarded, therefore, as the sole criterion in establish-

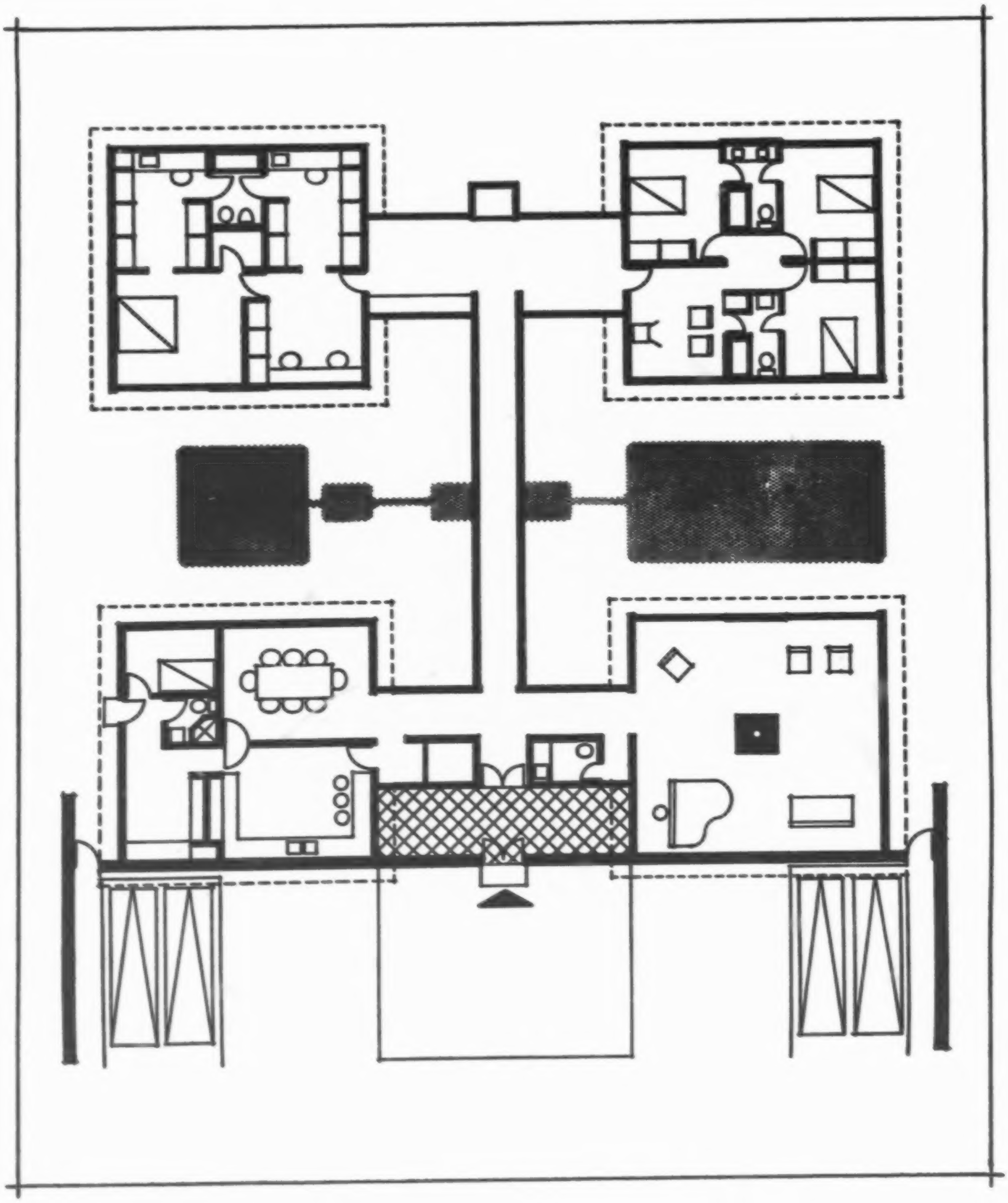


Figure M.8. Floor plan of an ideally zoned family house in Louisiana, clearly illustrating features of an acoustically ideal home. Colbert and Lowry, architects. (Reprinted from Community and Privacy by S. Chermayeff and C. Alexander, Doubleday and Co., Garden City, N.Y., 1963).

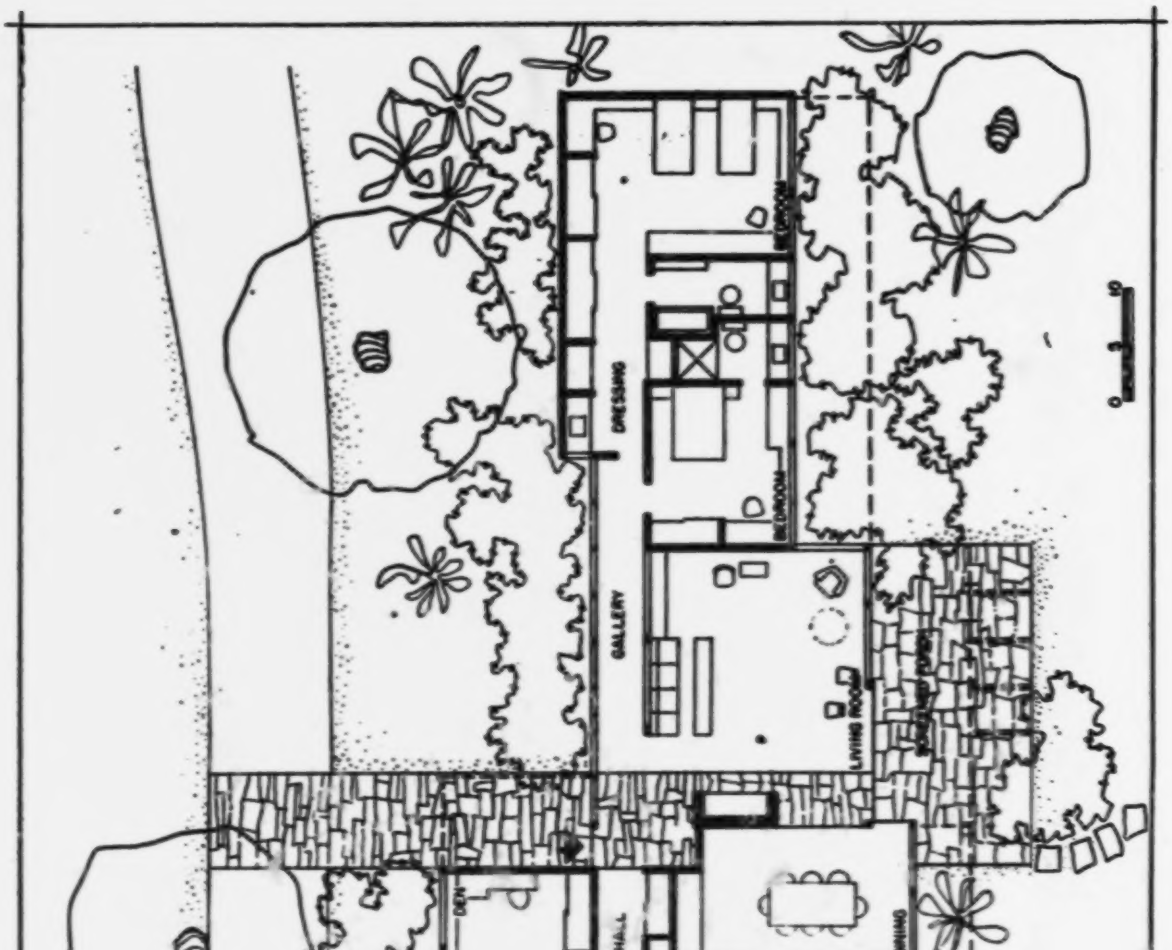

BEDROOM
DRESSING
BEDROOM
GALLERY
LIVING ROOM
DEN
ENTRANCE HALL
DINING
PANTRY
NOOK
KITCHEN
LAUNDRY
PORCH
BEDROOM
CARPORT
HELP
TOOLS

Figure M.9. Floor plan of a family house in Louisiana, with outstanding acoustical privacy. R.J. Neutra, architect. (Reprinted from Arch. Rec., May 1955).

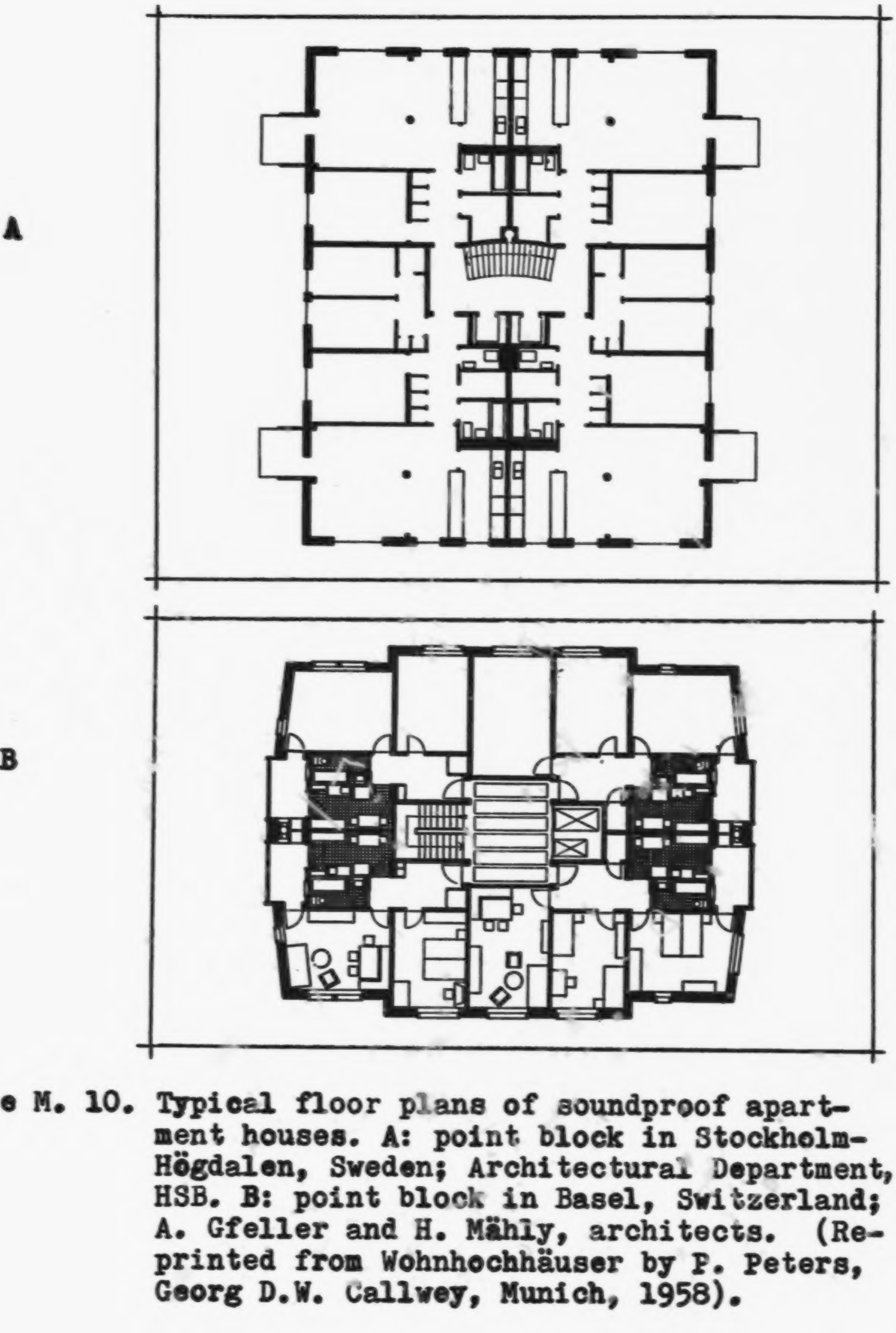


Figure M. 10. Typical floor plans of soundproof apartment houses. A: point block in Stockholm-Högdalen, Sweden; Architectural Department, HSB. B: point block in Basel, Switzerland; A. Gfeller and H. Mähly, architects. (Reprinted from Wohnhochhäuser by P. Peters, Georg D.W. Callwey, Munich, 1958).

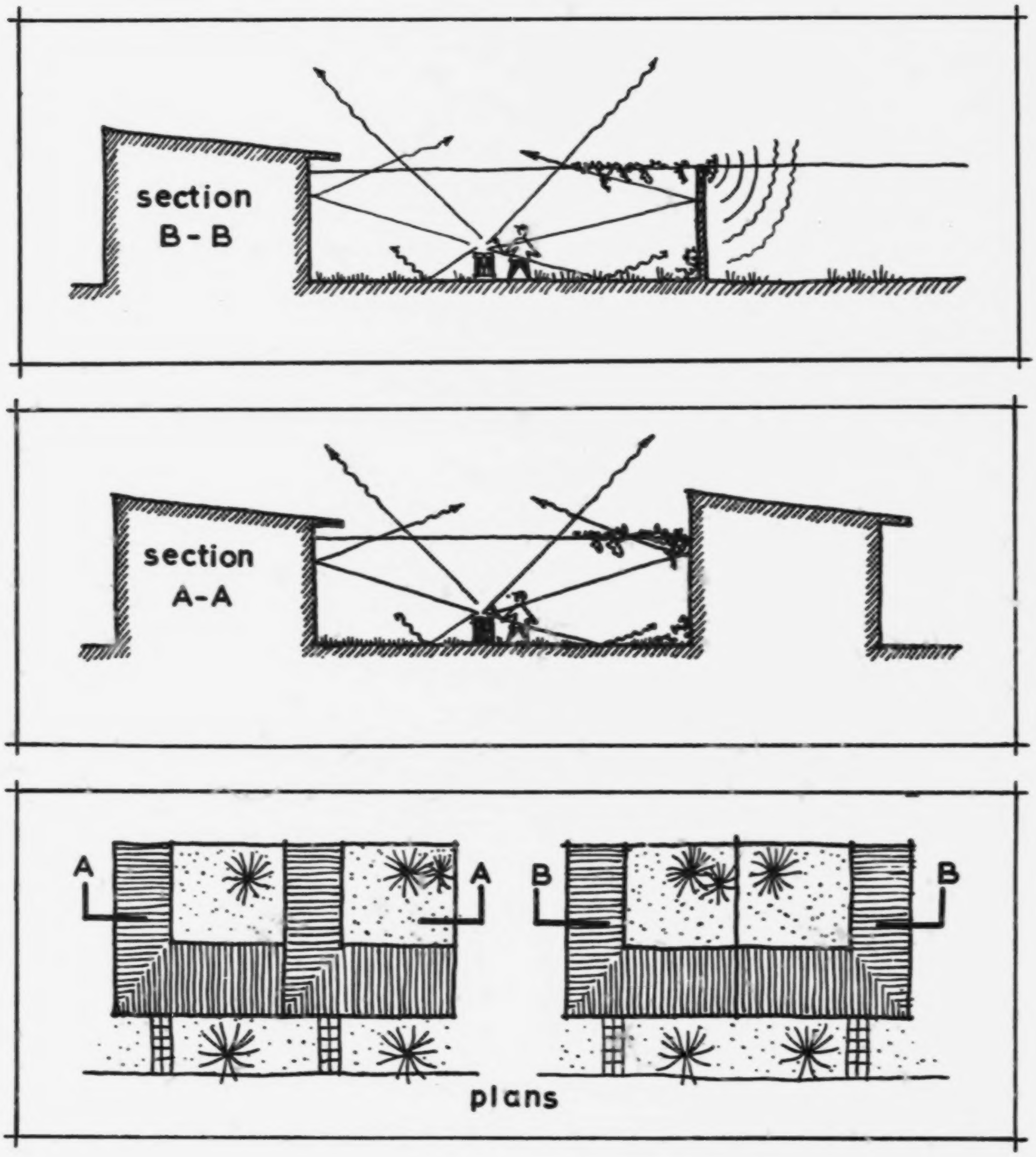

section
B-B
section
A-A
A
A
B
B
plans

Figure M. 11. Court-garden house providing a high degree of acoustical privacy. (Reprinted from The Court-Garden House by N. Schoenauer and S. Seeman, McGill University Press, Montreal, 1962).

ing its thickness. It must be realized that a 5" thick reinforced concrete slab in itself will just provide a bare acoustical minimum for the required horizontal separation between two occupancies; if a higher degree of acoustical privacy is aimed at, a thickness of more than 5" should be provided.

The thickness of wall established on the basis of its structural function alone often does not meet the requirement for adequate sound insulation.

When buildings have to be isolated against vibrations originating from adjacent railroad tracks, subways, underground Railway Stations, or highways with heavy traffic, anti-vibration pads are often used requiring a careful integration with the foundation of the respective building (N-41).

M.6.6 Noise control by means of mechanical design

Mechanical installations and equipment can be serious noise sources. The noise hazard will be greatly reduced if attention is given to following recommendations:

(a) in the selection of a suitable heating, ventilating or air-conditioning system and equipment,preference should be given to silently operating systems, fixtures, and equipments (S-41, GB-69);

(b) noise and vibration producing mechanical equipment (fans, motors, etc.) should be accommodated low down in the basement if possible. The load bearing structure associated with these equipments is likely to be heavy, providing a high degree of insulation against noises and vibrations at a location where this insulation is most needed (GB-43);

(c) pipes, ventilating ducts, continuous perimeter heating strips, etc.,can seriously affect, often nullify, the sound insulating efficiency of enclosures (M-122);

(d) fixtures recessed back-to-back in partition walls (medicine cabinets, switch and outlet boxes, etc.) should always be staggered to avoid direct transmission of sound through the partition wall in question (S-41);

(e) service pipes or mechanical appliances should not be located close to or recessed into enclosures designed to provide acoustical separation. These pipes should be resiliently anchored to walls or suspended from ceilings if they are likely to transmit noises or vibrations (M-122, S-41);

(f) ventilating louvres, if used, should incorporate noise filters (M-122).

The control of mechanical noises will be discussed in Section O.

M.6.7 Noise control by means of organization

If certain noises cannot be eliminated, or if it would be uneconomical to take corrective measures to achieve noise control, the situation can be remedied often by way of organization; e.g., certain rooms overly exposed to excessive noises can be regrouped or relocated.

Sometimes too many workers are affected unnecessarily by noisy machines scattered throughout a Workshop. If the individual machines cannot be modified, it will be advisable to consider the regrouping of the machines in a restricted area as far as possible from the rest of the space (GB-43).

In other cases, large noisy rooms should be partitioned off from the rest of the space.

Earplugs or muffs have to be used in excessively noisy areas where no other reasonable means of reducing the noise are available (M-78, R-27).

Anti-noise ordinances, if strictly enforced, constitute effective means of combatting community noise by means of organization (R-2); their discussion is beyond the scope of this study.

M.6.8 Noise reduction by means of sound absorptive treatment

It was mentioned in paragraph M.3.1 that the noise level in the receiving room is made up of the direct sound and the reflected or reverberant sound.

The noise level of the reverberant sound can be reduced to a limited extent only by the use of sound absorptive treatment. This reduction in the noise level due to the installation of sound absorptive treatment is given by the following formula (assuming that the sound field is diffused in the room):

$$\text{Reduction}_{\text{noise level}} = 10 \log_{10} \frac{A_2}{A_1} \quad \text{dB}$$

where A_1 and A_2 are the total absorptions of the room in ft^2 units before and after treatment, respectively (M-6, M-11, M-16). Figure M.12 will facilitate the estimation of the reduction in noise level; the change, i.e., the reduction in loudness level, is shown on the vertical axis, and depends on the increase in absorption units plotted on the horizontal axis (M-16). Figure M.12 clearly shows that it will be necessary to double the amount of existing absorption in the receiving room in order to obtain a reduction of 3 dB in the reverberant noise level. If, by installation of various acoustical materials, the absorption of the room can be increased by a factor of ten, the reverberant sound level will be reduced by 10 dB. Figure M.13 illustrates that a reduction of 3 dB in the noise level means a 22 % reduction in loudness, and a reduction of 10 dB in the noise level will produce a 54 % reduction in loudness (M-16, M-31, GB-43). This Figure also indicates that once a 10 dB reduction has been achieved, very little, if any, addi-

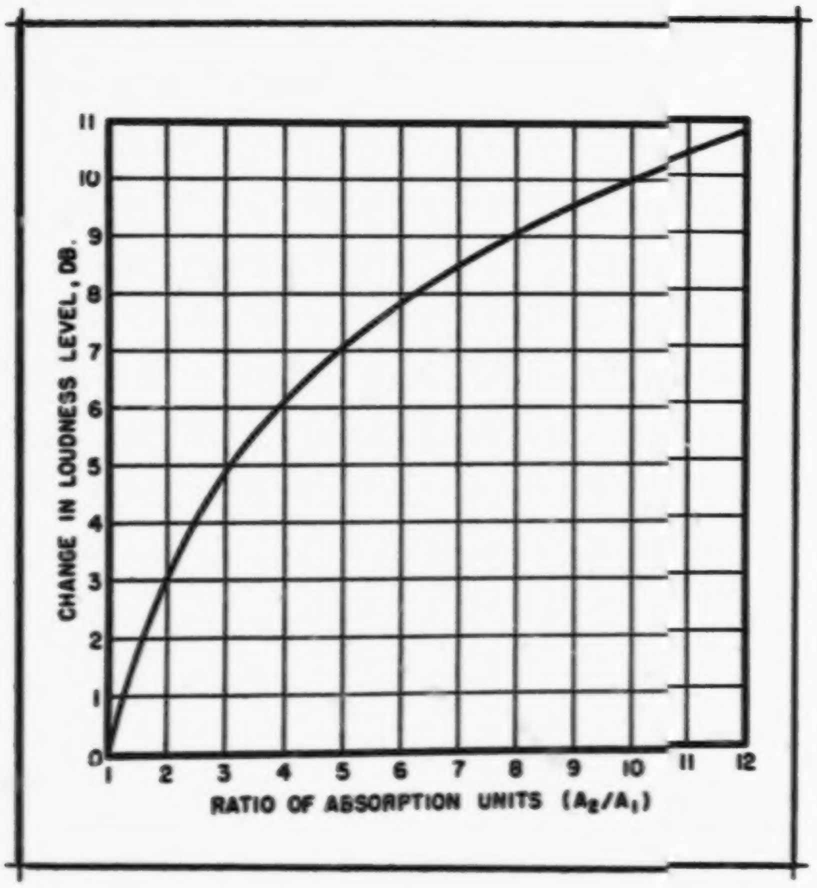


Figure M. 12.

Change (reduction) in loudness level due to the use of sound absorptive treatment in a room. (Reprinted from Noise Reduction Manual by P.H.Geiger, Engineering Research Institute, University of Michigan, 1956).

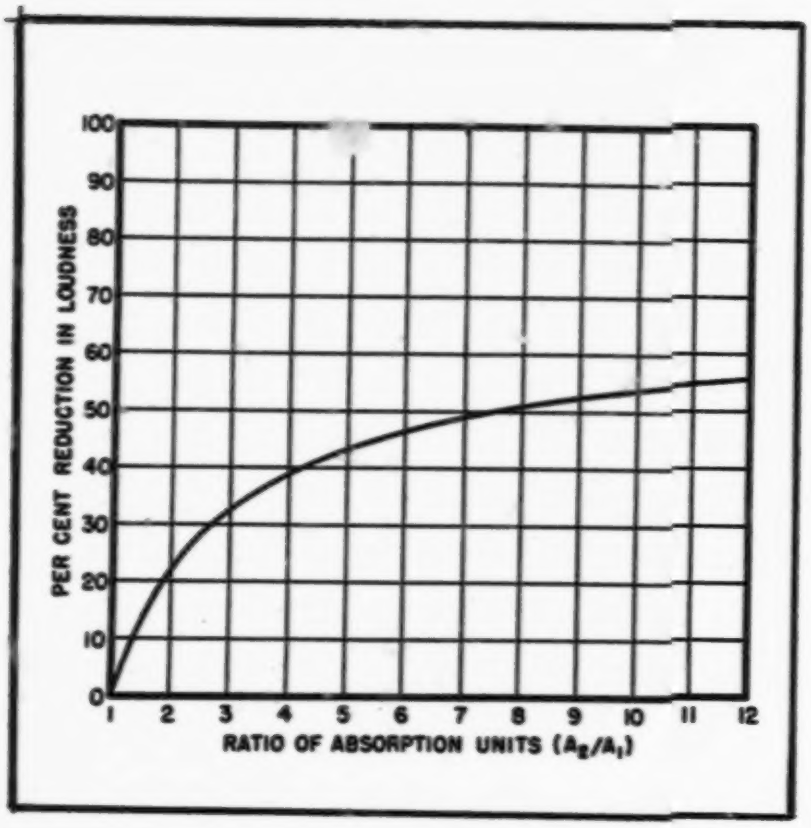


Figure M. 13.

Change (reduction) in loudness due to the use of sound absorptive treatment in a room. (Reprinted from Noise Reduction Manual by P.H.Geiger, Engineering Research Institute, University of Michigan, 1956).

tional reduction in noise level can be expected in a room by the use of sound absorptive treatment.

The use of sound absorbing materials in the receiving room should not be regarded as a substitute or cure for deficient sound insulation (M-6).

Introducing as much sound absorptive treatment as is convenient in the receiving room has the following advantages (M-6, M-8, M-11, M-79, M-126, S-141, S-149, S-163, GB-43):

(a) the receiving room will be quieter except for those located in the direct sound field;

(b) it will reduce the overall sound level. Less sound energy will fall on the room enclosures which will result in reduced noise transmission to adjacent rooms. The acoustical power expended on speaking can be reduced, etc.;

(c) it will tend to localize noises to the area of their origin. This is particularly advantageous in Workshops with machines of various noise levels; the operator of a relatively quiet machine will not be so annoyed by the noise from a noisier but remote unit;

(d) the R.T. will be reduced in the room; this is particularly beneficial in rooms with transient noises (e.g., a burst of riveting, a hammer stroke, etc.), because the reverberation of these transient noises will be reduced. In addition, this will permit better mental localization of sound sources, reducing the feeling of confusion,and improving the sense of well-being for workers in noisy rooms.

The sound absorbing materials to be used for noise reduction purposes in a room are the same as those described in Section E (M-62, M-114). The absorbents should be installed as close as possible to the noise sources. If available room surfaces do not provide sufficient area for sound absorbing materials, the use of space absorbers is recommended (subsection E.4).

Since the sound absorption coefficient of acoustical materials vary with frequency, the noise reduction achieved will also be different at various frequencies (M-6, M-11). This must be considered in the selection of appropriate absorbent treatment (M-79).

M.6.9 Noise control by means of sound insulating building construction

This will be the subject of Section N.

M.6.10 Noise control with masking noise

In many situations annoying noise control problems can be cured only by drowning out (or masking) unwanted noises by the use of artificially created background noise. This artificial noise is often referred to as "acoustical perfume", even though the term "acoustical deodorant" would be more appropriate; it will suppress minor intrusions which might interrupt the recipients' privacy.

Noise from ventilating systems, from traffic or from general office activities will contribute to the production of artificial masking noise (O-86, R-6, R-13, R-15, R-22, S-15, GB-69).

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relative to Section M: " General Principles of Noise Control"

(See list of abbreviations on page 1)

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Section N. Sound Insulating Building Constructions

- N.1 Insulation against air-borne sound
    - N.1.1 Transmission loss
    - N.1.2 Single-leaf partitions
    - N.1.3 Multiple partitions
    - N.1.4 Composite partitions
    - N.1.5 Measurement of transmission loss
    - N.1.6 Noise reduction of enclosures
- N.2 Insulation against structure-borne sound. Measurement of impact noise
- N.3 Sound insulating building constructions
    - N.3.1 Walls
    - N.3.2 Floors, ceilings
    - N.3.3 Doors
    - N.3.4 Windows
    - N.3.5 Discontinuous construction
- References

If none of the noise control methods, described briefly in subsection M.6, can be followed, then the transmission of air-borne noises, structure-borne noises, impact noises, or vibrations, can be intercepted only by the use of sound insulating enclosures including walls, floors, doors and windows (N-1, N-2, N-3, N-4, N-5, N-6).

In subsequent discussions, the term "partition" means any enclosure (wall, floor, door, or window) that separates horizontally or vertically either source room from receiving room or any other two spaces.

N.1 Insulation against air-borne sound

N.1.1 Transmission loss

The transmission loss (abbreviated: TL) of a partition, stated in decibels, is a measure of its sound insulation (GB-73); it is equal to the number of decibels by which sound energy incident on the partition is reduced in transmission through it. The numerical value of the TL depends on the construction of the partition only; it is independent of the acoustical properties of the two spaces separated by the partition (N-1, N-3, N-32, N-54, N-93, N-126, GB-21, GB-34).

N.1.2 Single-leaf partitions

The TL of homogeneous single-leaf partitions that are damped (so that they do not ring when struck with a hammer) will depend primarily on the product of the surface weight of the partition, measured in lb per ft^2, and the frequency. The TL of such partitions can be determined from the mass law curve, illustrated in Figure N.1 (GB-34). This curve assumes that the sound hits the partition uniformly from all directions (random incidence). The Figure shows that for damped,

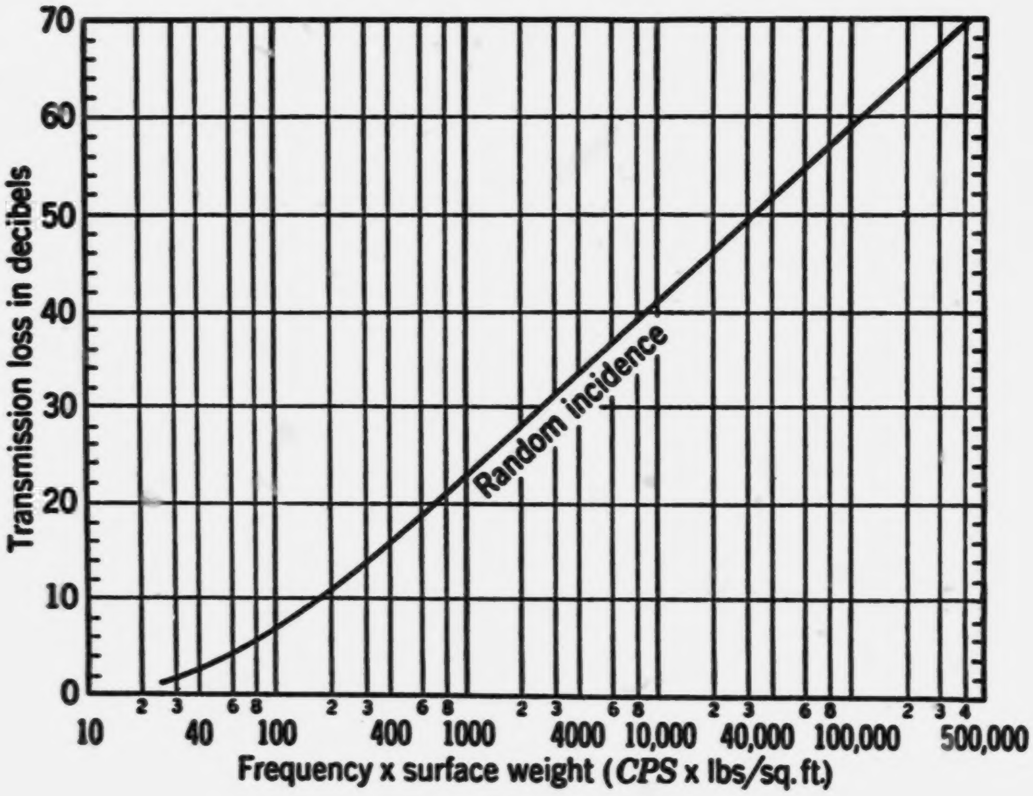

Figure N.1. Transmission loss for solid damped single-leaf partitions. The average TL may be determined from this graph by assuming a frequency of 500 cps. (Reprinted from Acoustics by L.L. Beranek, McGraw-Hill Book Co., New York, 1954).

single-leaf partitions the TL increases about 5 dB for each doubling of frequency or doubling of weight (N-4, N-54, N-126, GB-34, GB-43).

Table N.1 shows the surface densities of common building materials, per 1" thickness (N-70, GB-34).

Table N.1. Surface densities of common building materials, per 1" thickness

Material	Surface weight, lb/ft^2
Acoustic tile	1-1.5
Aluminum	14
Asbestos board (Transite)	9
Brick	9-12
Concrete	
dense	12
cinder	6-9
Haydite	7-8
Vermiculite	2-7
Cork board	0.7
Glass	13
Gypsum	5
Hollow clay tile	4-6
Lead	59
Plaster	
light-weight aggregate	5
sand aggregate	9
Steel	40
Wood	
timber	2-5
fir plywood	3

It must be noted that the TL for single-leaf partitions, regardless of their weights, cannot be increased limitlessly because of unavoidable paths of flanking transmission (discussed in paragraph N.1.6, and illustrated in Figure N.4).

To achieve an effective TL of a partition, it is necessary that it be impervious to air flow. Walls built of various porous concrete blocks will not yield a TL in accordance with their weight and predicted from Figure N.1, due to their porosity. However, the TL of a porous partition may be considerably improved by the use of a sealant (plaster, oil paint, cement-base paint, etc.) on its exposed surfaces (E-6, N-32, N-141).

There is a limitation of the mass law curve, shown in Figure N.1, brought about by a special condition called coincidence effect. Under this condition,the effective TL of a partition will be considerably lower at certain frequencies than the mass law would predict (N-70, N-126). The coincidence effect becomes detrimental if the critical frequency range (called coincidence frequency), at which the partition is substantially transparent to the passage of sound, falls in the range of audibility. The coincidence effect can be reduced or limited if the coincidence frequency can be kept outside the important subjective range of frequencies; this will be achieved by the use of thick and very stiff walls or by heavy and limp walls, with reduced stiffness (M-18, N-70, N-97).

Additional information on the methods of improving the TL of partitions is available from many sources (N-9, N-12, N-73, N-75, N-84, N-86, N-98, N-111, N-136, N-141, N-144, N-154).

N.1.3 Multiple partitions

To achieve a significant improvement over the basic TL of a single-leaf partition, it will require doubling or tripling its mass. An increase of this extent in the weight and thickness of an enclosure is obviously prohibitive, due to its functional, spatial, structural, and hence economical consequences.

If a high degree of sound insulation is required, it will be advisable, therefore, to use a partition of multiple construction, built of two or three separated leaves (M-6, N-1, N-2, N-3, N-4, N-23, N-32, GB-52).

Multiple partitions will provide a higher TL than would be expected from their weight alone, particularly at the higher frequencies, (a) if the separation between the leaves has been consistently secured, (b) if the distance between the leaves has been reasonably determined, (c) if sound absorbing material is properly mounted in the air space, and (d) if an efficient sound insulating or vibration isolating material is used between the leaves of the partition and the building structure (M-6, N-32, GB-21). Figure N.2 shows the improvement in TL for multiple partitions with air space over single leaf partitions of the same total weight (N-126).

It must be noted that the curves shown in Figure N.2 do not indicate certain, sometimes surprising, dips which might occur in the TL of multiple partitions at certain frequency ranges, as a result of a resonance effect. This is caused by the coupling of the two leaves, partly due to the air space between the leaves,and partly due to the structural connection between the leaves. By selecting the proper material and thickness of the leaves with adequate separation between them, the resonance effect can be minimized and shifted to less critical frequency ranges (N-37, N-126, GB-52).

N.1.4 Composite partitions

If a door, window or opening has to be incorporated into a wall, the overall sound insulation of the resulting composite partition is determined primarily by its weakest link.

Various methods and simplified diagrams are available for the rapid calculation of the composite insulation of partitions made up of several elements with differing TL values (M-18, N-1, N-76, N-126, GB-34).

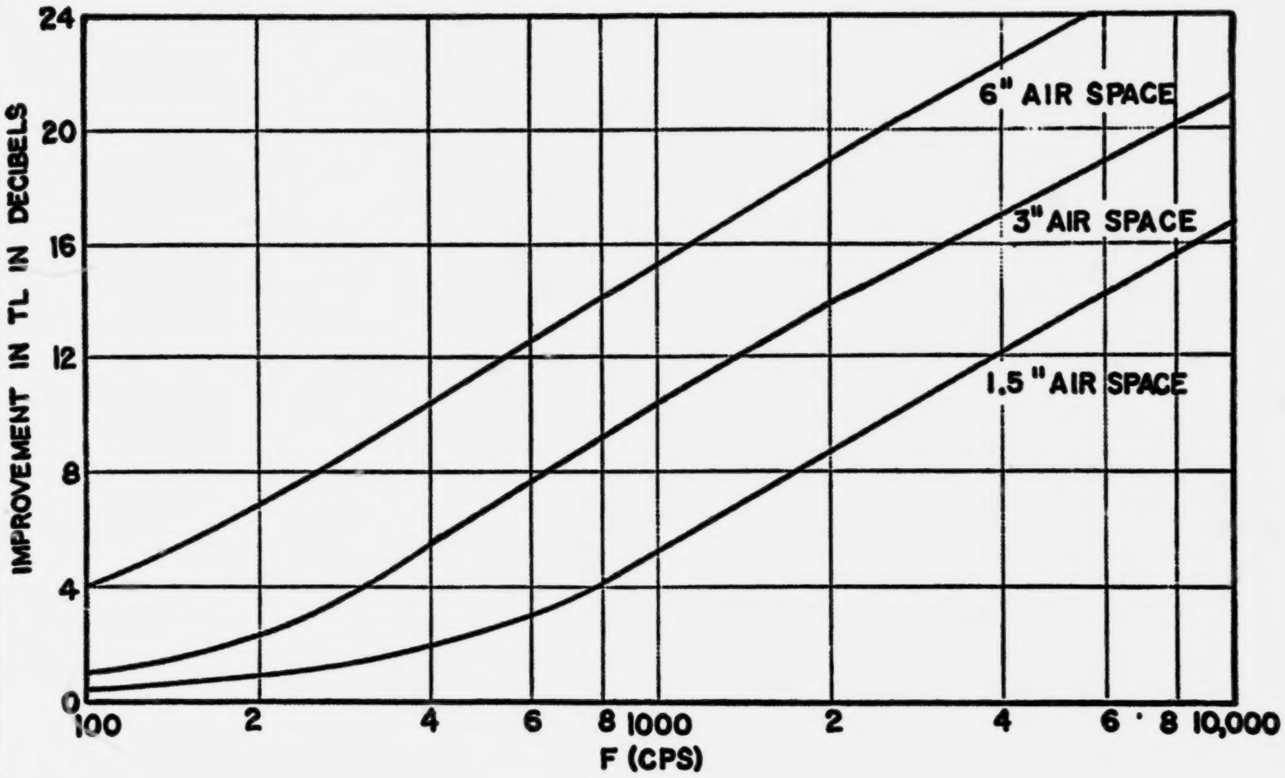

Figure N.2. Improvement in TL for multiple partitions with air space, over single-leaf partitions of the same total weight. (Reprinted from Noise Control, July 1957).

N.1.5 Measurement of transmission loss

The air-borne sound insulation of any partition varies with frequency, and it is therefore necessary that TL measurements be made over a frequency range covering those frequencies likely to be important in noise control problems. Measurement of TL can be made in a laboratory or in the field (N-32, N-126).

For laboratory measurement of the TL of various enclosures (walls, floors, doors, windows, etc.) contemporary testing facilities are available at the National Research Council, in Ottawa (Division of Building Research). In the U.S.A., the following are considered as accredited testing laboratories for the measurement of TL: the National Bureau of Standards in Washington, D.C.; the Riverbank Acoustical Laboratory in Geneva, Ill.; and the Geiger and Hamme Laboratory at the University of Michigan.

For laboratory measurement, the test specimen, which is to typify an enclosure, must be large enough to include all the essential constructional elements. It is usually installed in a manner as similar as possible to an actual construction. Measurements of TL are normally made at the following nine frequencies: 125, 175, 250, 350, 500, 700, 1000, 2000 and 4000 cps. Test results are issued in the report of the laboratory, including the following (M-18, N-94, N-126):

(a) description of the test specimen and all the essential constructional elements (composition of plaster mixes, methods of application, surface finish, etc.);

(b) test specimen size, including thickness, weight per ft^2 of surface, and mounting conditions;

(c) test results reported as the TL at the frequencies listed above. If an average TL is reported it should be the arithmetic mean of the values obtained at these nine test frequencies;

(d) a statement whether measurements have been performed by means of warbled tones or by noise (paragraph E.9.2);

(e) a statement that the test was conducted in accordance with the latest ASTM Standard; any deviation from the recommended practice will be listed in the report and explained.

Average TL values, included in laboratory reports, provide a simple and convenient method of rating for quick acoustical evaluation of enclosures. However, an average TL of the nine test frequencies does not always exhibit an unambiguous picture of the acoustical performance of the partition under consideration. For example, two different partitions with different transmission losses at vital frequency readings but with the same average TL value, could be erroneously considered as acoustically identical constructions against air-borne noises if their average TL were regarded as a characteristic of their sound insulative performance. Diagrams "A" and "B" in Figure N.3 show the TL curves of two such partitions, both having by chance a nine frequency average TL rating of 30 dB. On the basis of their average TL ratings these two partitions seem to be equal even though partition "B" shows a serious deficiency (dip) in the vital frequency range of 700 to 1500 cps.

To avoid the often misleading attribute of an average TL value, the revised ASTM Standard E 90-61T has adopted a new type of single-figure rating, called the Sound Transmission Class (abbreviated: STC) contour which insures that at no frequency will the TL of a partition be less than the level corresponding to the STC, thus eliminating ambiguities of an average TL value. Plotted on a conventional (semilog) paper, the STC contours consist of horizontal segments from 1400 to 4000 cps, at a level corresponding to the STC; a middle segment that decreases 6 dB from 1400 to 350 cps; and a low frequency segment that decreases 14 dB from 350 to 125 cps (N-95). STC contours 30 and 19 are shown on diagrams "C" and "D" respectively of

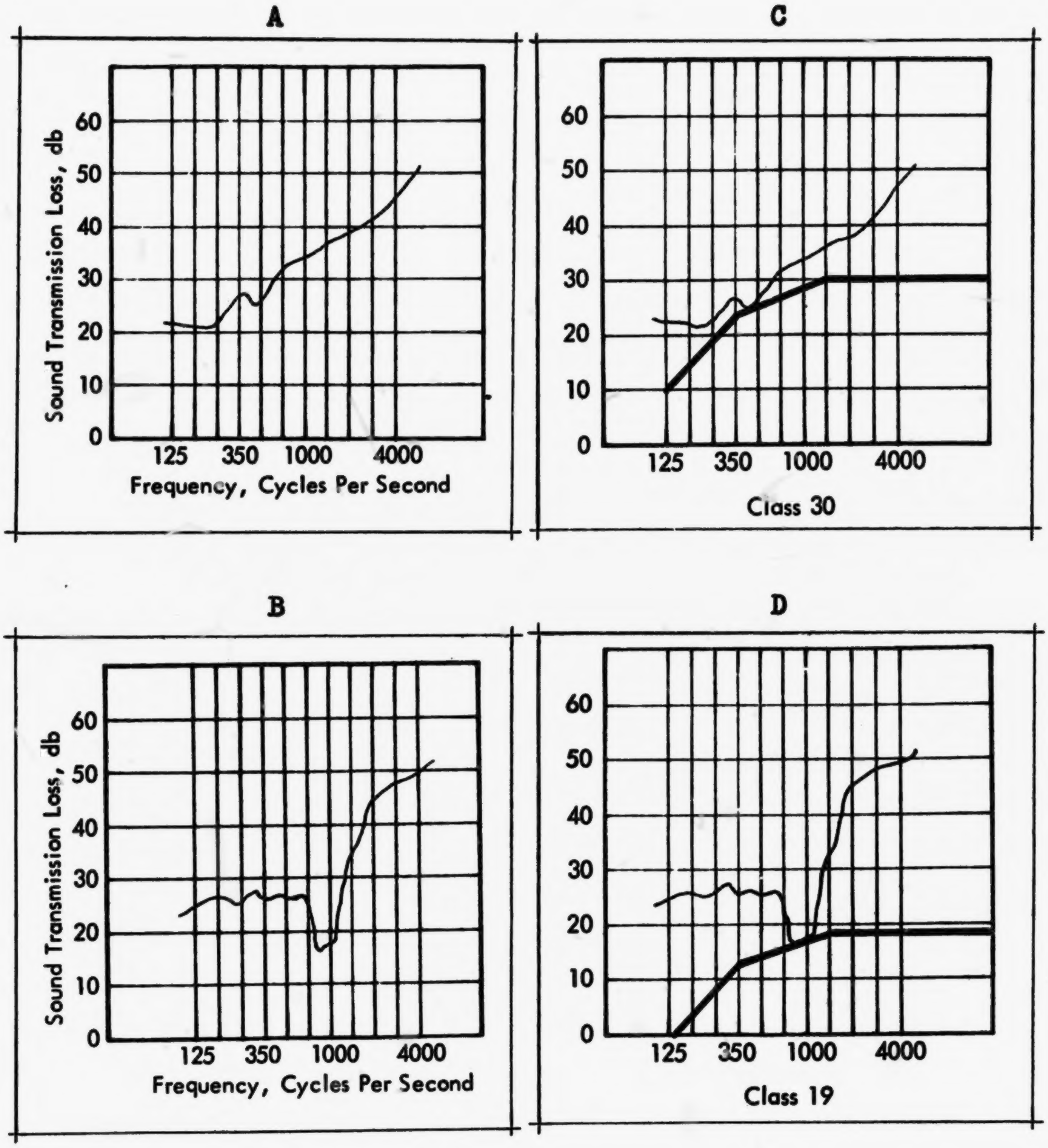

Figure N.3. The average TL of a partition often does not represent a true characteristic of its insulating performance against air-borne sounds. Average TL values of partitions "A" and "B" are the same, both having an average TL of 30 dB. Corresponding STC contours "C" and "D", however, reveal the superiority of partition "A" over partition "B". (Reprinted from Freedom from Distraction, Hough Manufacturing Corporation, Janesville, Wisconsin, 1963).

Figure N.3, as corresponding contours to partitions "A" and "B", respectively, overlaid on the corresponding TL curves. It will be obvious from these diagrams that partition "A", representing an STC of 30, is far superior to partition "B" which represents an STC of 19 only.

According to revised ASTM Standard E 90-61T, two ratings are given for each product in the laboratory reporting:

(a) the STC, and

(b) the nine frequency arithmetic average, for comparison with previous data and for dealing with specifications still based on this index.

The preferred criterion, however, is the STC rating.

A slight increase in the accuracy of an average TL figure can be provided by making an approximate allowance for the average increase in insulation per octave, i.e., for the "slope" of the insulation. It has been found that a slope of 10 dB per octave makes a partition 2.5 to 3 dB less effective in reducing the loudness of speech or music than a partition of the same average TL but with a slope of 5 dB per octave (R-4).

Even though laboratory tests for the measurement of TL are conducted under ideal testing conditions and according to a predetermined, well organized procedure, it is the field measurement that can tell the actually achieved isolation designed on the basis of laboratory TL data (N-66). Experience has proved that the noise reduction of partitions achieved on the job frequently falls short of the degree predicted on the basis of laboratory tests. This happens because (a) the size of the partition being measured in the field is usually different from the test sample, and (b) there is always some difference between edge-fixing conditions in the field and in the laboratory. In the field, the sound leakage through unpredictable flanking paths may be comparable to or greater than that transmitted through the partition itself. In spite of these discrepancies,field measurements still constitute an important tool in the evaluation of the acoustical performance of enclosures (N-59, N-66).

Additional information on the measurement of TL of various enclosures is available from many sources (N-8, N-11, N-13, N-15, N-20, N-21, N-22, N-29, N-30, N-37, N-51, N-58, N-61, N-64, N-69, N-74, N-78, N-99, N-159).

N.1.6 Noise reduction of enclosures

It has been mentioned that the TL is determined by the physical properties of a partition, irrespective of the acoustical properties of the rooms separated by the partition.

Noise reduction (abbreviated: NR) is a more general term than TL for specifying sound insulation between rooms because it takes into account the effects of the various transmission paths between source room and receiving room and also the acoustical properties of these rooms (N-16, N-52, N-54, N-55, N-126, GB-34).

The NR, expressed in decibels, is given by the following formulae (N-126):

$$NR = SPL_1 - SPL_2 \text{ , or}$$

$$NR = TL + 10 \log_{10} \frac{A_2}{S_w}$$

where SPL_1 and SPL_2 are the average sound pressure levels (measured by a sound level meter) in the source room and in the receiving room, respectively,

A_2 is the total acoustical absorption, in ft^2 units, in the receiving room (as described in subsection D.5), and

S_w is the area of the partition, in ft^2, common to both rooms.

The NR may be larger or smaller than the TL, depending on the relationship between acoustical absorption and partition area in the receiving room. If all boundary surfaces in the receiving room are completely absorbent, the NR will exceed the TL by 6 dB, in which case NR = TL + 6 dB.

Various nomograms are available in the published literature for quick determination of the NR between two rooms (N-126).

The NR provided by a partition between source room and receiving room will be reduced mostly by the so-called "flanking transmission", i.e., the sound traveling through any of the following flanking paths (N-40, N-42, N-54, N-82, R-15):

- side walls;
- floors;
- openings in the partition created by joints between prefabricated, or movable elements, cracks, etc.;
- joint between partition and mullion;
- openings in the partition for doors or windows;
- ceiling plenums, perforated ceilings without noise barriers, cross-connected ceiling ducts;
- openings in the partition necessitated by wiring, plumbing, heating, ventilating or air-conditioning ducts and recessed fixtures;
- cross-connected (continuous) heating units;
- spandrel beams.

Many of these paths of transmission are illustrated in Figure N.4 (N-32, R-15).

N.2 Insulation against structure-borne sound. Measurement of impact noise

Insulation against structure-borne noise or impact noise, as described in paragraph M.5.2, will be achieved by the use of (a) a soft floor finish, or (b) a floating floor (paragraph

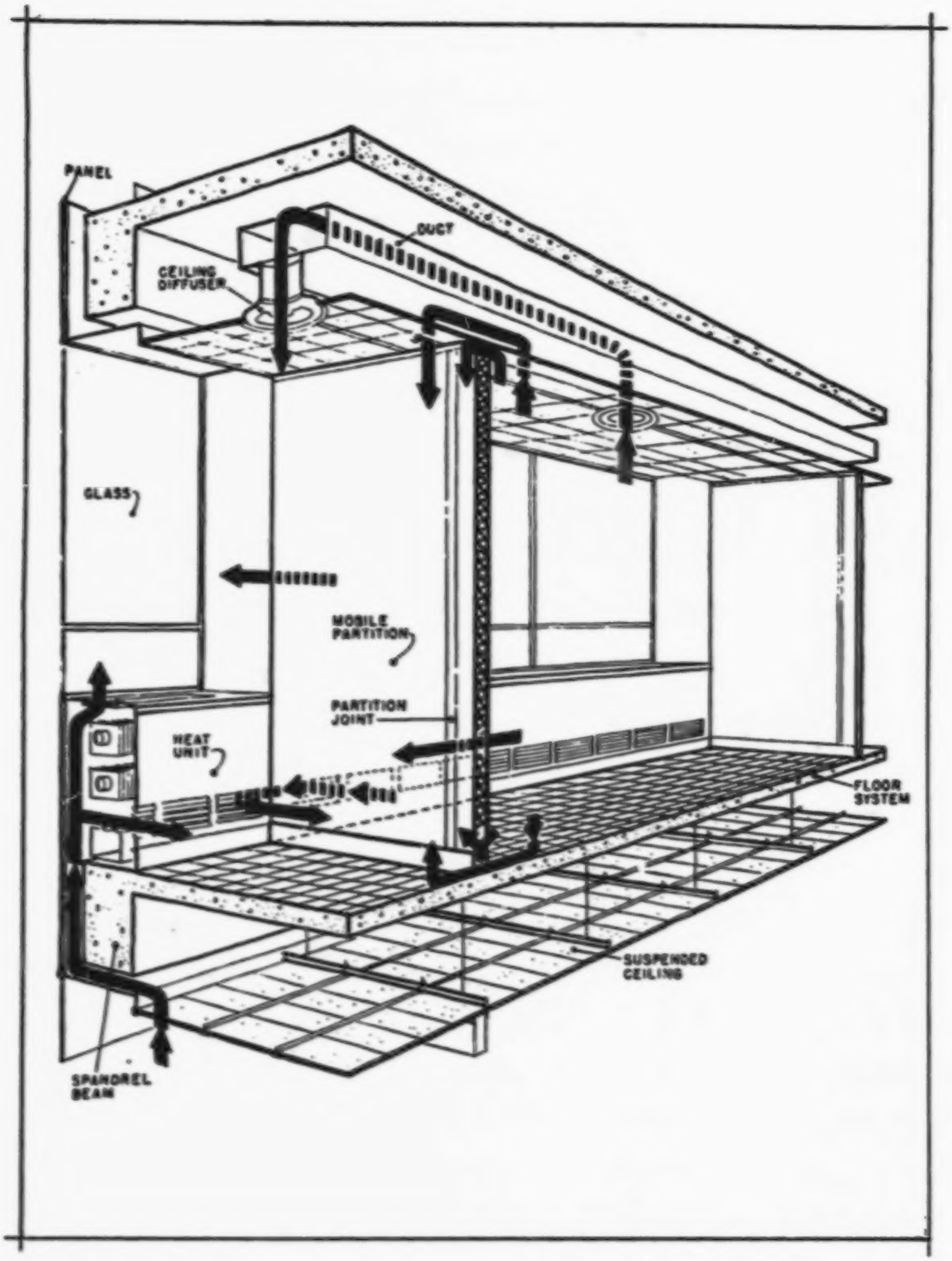
PANEL
DUCT
CEILING DIFFUSER
GLASS
MOBILE PARTITION
PARTITION JOINT
HEAT UNIT
FLOOR SYSTEM
SUSPENDED CEILING
SPANDREL BEAM

Figure N.4. Transmission of noise between adjacent rooms through flanking paths. (Reprinted from Arch. Rec., June 1959).

N.3.2). A soft floor finish does not provide extra insulation against air-borne sounds; a floating floor, on the other hand, will improve the air-borne sound insulation of an enclosure (N-1, N-3, N-33, N-53, N-160, GB-29, GB-43, GB-52).

The measurement of impact noise is quite different from that of air-borne noise. The insulation against impact noise provided by a given floor can be determined by means of a standard "tapping" machine which produces a series of uniform impacts at a uniform rate on the floor under test (N-59, N-160, GB-29, GB-52). The impact sound pressure levels will be measured in the receiving room below and analyzed into bands of frequency so that a curve can be plotted showing sound levels in the receiving room. The lower the measured sound levels are in the receiving room, the more insulative the floor is against impact noise. Figure N.5 illustrates the practical application of the tapping machine (N-160). This Figure shows a curve of maximum acceptable impact sound pressure levels for floor constructions in built Apartment Houses, due to tapping the floor overhead with the standard tapping machine, as recommended by the Federal Housing Administration (Washington, D.C.). Since the tapping machine might be used in differently furnished apartments, the FHA recommends that the measurements be normalized to a receiving room R.T. of $T_0 = 0.5$ sec; this is necessary because the amount of sound absorbing material in the receiving room will have an effect on the measured sound levels (as described in paragraph M.6.8).

Additional information regarding the research work on impact noise has been presented in several articles (N-14, N-22, N-26, N-44, N-47, N-48, N-60, N-161, N-167, N-171, N-185, N-202).

Vibration control will be discussed in Section P.

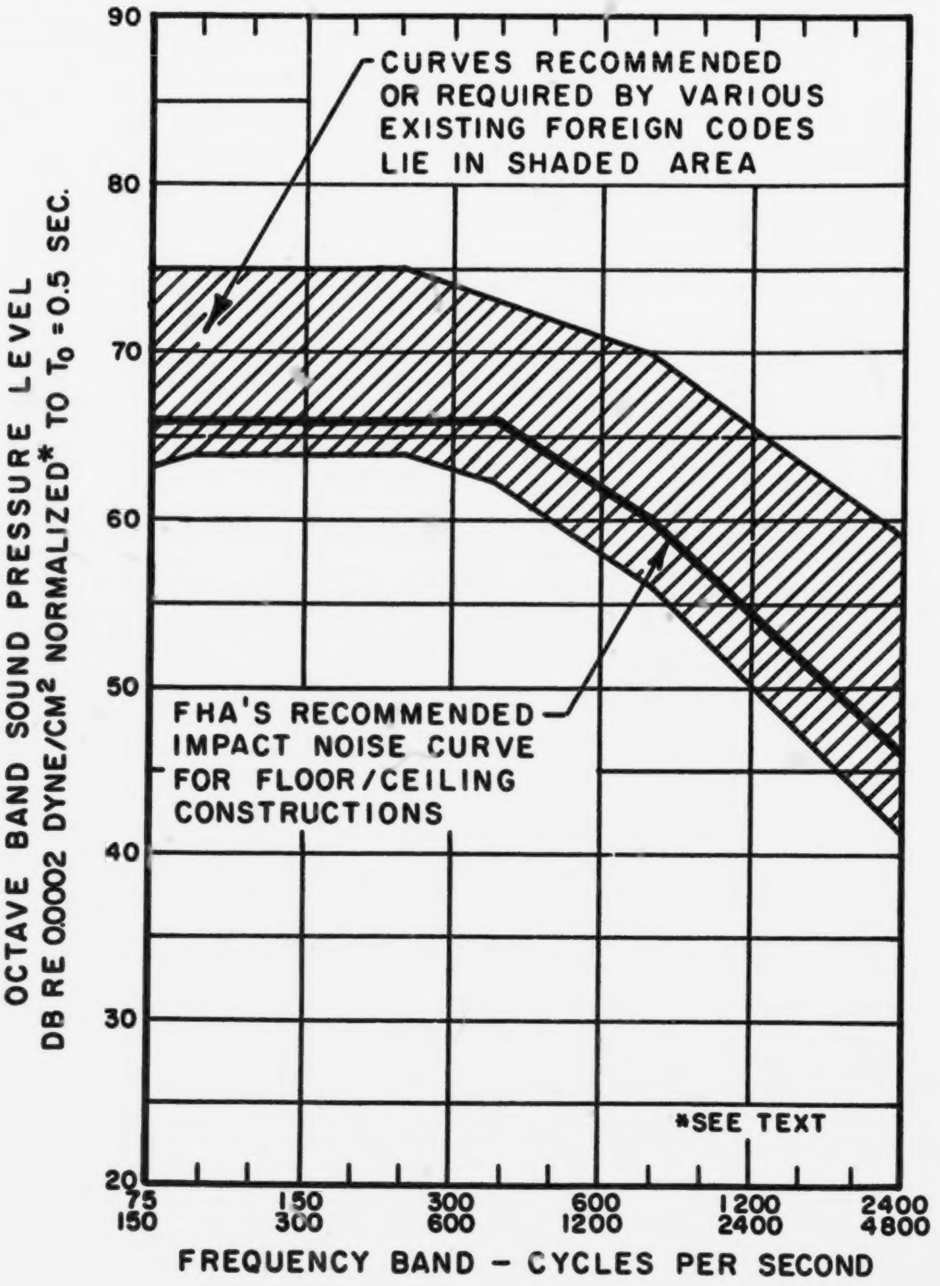

Figure N.5. According to FHA recommendations impact sound pressure levels in the receiving room below floor construction of Apartment Building, on which a standard tapping machine is operating, should not exceed the curve shown in heavy line. (Reprinted from Impact Noise Control in Multifamily Dwellings by Bolt, Beranek, and Newman Inc., Cambridge, Mass., Jan. 1963).

N.3 Sound insulating building constructions

N.3.1 Walls

It cannot be stressed too strongly that maximum insulation against air-borne noise cannot be expected from a partition wall, unless (N-96, N-105, N-113, N-150, N-151, R-15):

(a) it is installed as a complete, uninterrupted barrier;

(b) it is effectively sealed around its edges and between its elements, if any;

(c) it has uniformly distributed mass over its entire area; and

(d) it is either built from structural slab to structural slab, or, if constructed up to a suspended ceiling only, adequate measures have been taken for the acoustical restoration of its missing portion above the suspended ceiling.

Figure N.6 shows average TL values for various typical single-leaf and multiple partitions (walls and floors) measured in laboratories and in the field. The TL values of the partitions are arithmetic averages of the measured transmission losses at a number of representative frequencies, mostly extending from 125 to 2000 cps. The vertical height of each partition construction illustrated represents the range of TL that may be encountered in practice.

Table N.2 lists average air-borne transmission losses of typical wall constructions (M-122).

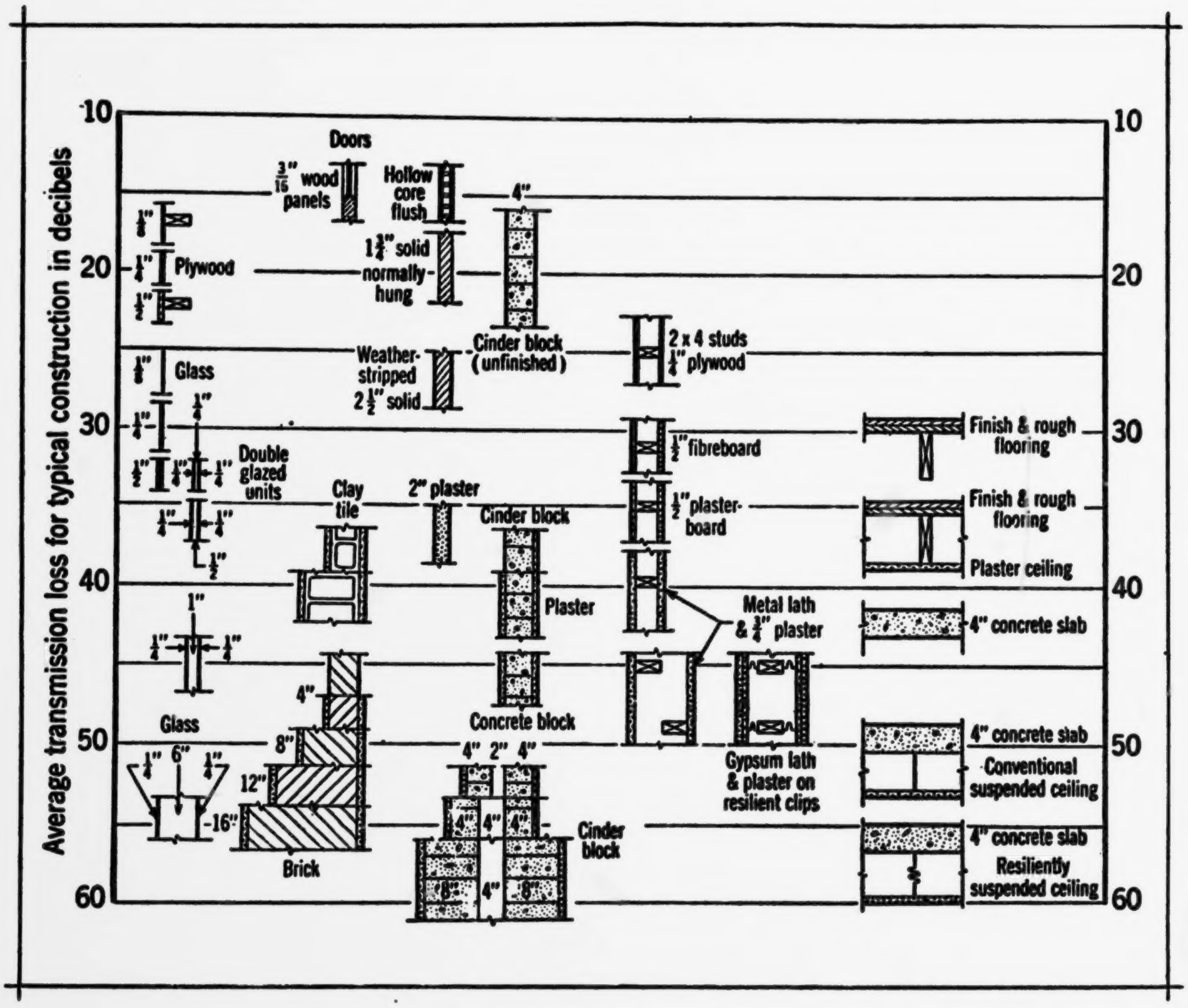

Figure N.6. Average transmission losses for typical single-leaf and multiple partitions as measured in laboratories and in the field. The vertical height of each construction shown in the Figure represents the range of TL that may be expected in practice. (Reprinted from Acoustics by L.L. Beranek, McGraw-Hill Book Co., New York, 1954).

Table N.2. Average TL of typical wall constructions for air-borne noises. (Reprinted from Noise Transmission in Buildings by T.D. Northwood, Canadian Building Digest, Division of Building Research, National Research Council, Ottawa, Oct. 1960).

A. Transmission loss 50 dB or more. (Recommended between critical areas of adjoining dwellings).

1. Single masonry wall weighing at least 80 lb/ft^2 including plaster if any.
2. Masonry cavity wall - 2 leaves of masonry spaced at least 2" apart, each leaf weighing at least 20 lb/ft^2 ● ; leaves tied together with butterfly ties at 2 ft centres.
3. Composite wall - basic wall masonry weighing at least 22 lb/ft^2 ● ; on one side of basic wall an additional leaf consisting of ½" gypsum lath mounted with resilient clips, ¾" sanded gypsum plaster.
4. Stud wall - 2" x 4" studs; on each face ½" gypsum lath mounted with resilient clips, ½" sanded plaster; paper-wrapped mineral or glass wool batts between studs.
5. Staggered stud wall - 2" x 3" studs 16" o.c. on common 2" x 6" plate; on each face ½" gypsum lath, ½" sanded gypsum plaster; paper-wrapped mineral or glass wool batts between one set of studs.

B. Transmission loss 45 to 49 dB. (Recommended between non-critical areas of adjacent dwellings.)

1. Single masonry wall weighing more than 36 lb/ft^2 including plaster if any ●.
2. Composite masonry - as in A.3 except gypsum lath supported on furring.
3. Staggered stud dry wall - 2 sets of 2" x 3" studs 16" o.c. on common 2" x 4" plate; on each face 2 layers of 5/8" gypsum wallboard, the first layer nailed, the second cemented; joints staggered and both sets sealed; mineral or glass wool blanket or batts in the interspace.

(Table N.2 cont'd.)

C. Transmission loss 40 to 44 dB.

   1. Single masonry wall weighing at least 22 lb/ft^2 including plaster if any.

D. Transmission loss 35 to 40 dB.

   1. Stud wall - 2" x 3" or 2" x 4" studs, 3/8" gypsum lath and ½" sanded gypsum plaster.
   2. Stud wall - 2" x 3" or 2" x 4" studs, 2 layers of 3/8" plasterboard, the first layer nailed, the other cemented; joints staggered.

● If porous blocks are used one face of each block section must be sealed with plaster or heavy paint.

Additional published information on the acoustical performance of various wall constructions is available from many sources (N-1, N-3, N-4, N-6, N-28, N-32, N-41, N-42, N-65, N-69, N-70, N-85, N-86, N-96, N-97, N-99, N-100, N-104, N-106, N-107, N-109, N-110, N-111, N-112, N-115, N-119, N-120, N-121, N-122, N-124, N-126, N-127, N-128, N-131, N-133, N-134, N-136, N-137, N-142, N-143, N-148, N-150, N-154, S-35, GB-3, GB-6, GB-9, GB-19, GB-20, GB-21, GB-25, GB-27, GB-28, GB-29, GB-52, GB-61, GB-62).

N.3.2 Floors, ceilings

A good floor will provide both satisfactory air-borne and impact sound insulation. A floor that ensures an acceptable noise level (in the room below the floor under consideration) due to impacts, might be unsatisfactory as regards air-borne sound insulation. On the other hand, a very heavy bare concrete floor will give satisfactory insulation against air-borne noises but will not necessarily provide an acceptable insulation against impact noises from the room above (N-33).

The most common floor constructions are:

(a) wood joist floors (N-33, N-70, N-128);

(b) structural concrete floors (N-33, N-70, N-128);

(c) floors supported by steel joists.

The sound insulating quality of floors can be improved as follows (N-165):

(a) by the use of a soft, resilient surface; this has negligible effect on the air-borne sound insulation of the floor;

(b) by using a floating floor; this provides substantial improvement against impact noise and a useful increase against air-borne noise;

(c) by installing a suspended ceiling; this will improve the insulation against both air-borne and impact noises by an amount depending on the weight of the suspended ceiling and the degree of rigidity with which the ceiling is attached to the structural floor.

Floating floors are supported (a) either by a continuous layer of resilient blanket, or (b) by sleepers that can rest on the resilient blanket or can be carried in resilient chairs (Figure N.11). In both cases, the floating floor assembly rests on the structural slab.

For a floating floor to secure the required acoustical performance, its natural resonant frequency should be as low as possible, and preferably below the lower limit of the audiofrequency range. This will be achieved if thickness and weight of the floating part and the elasticity of the resilient blanket have been properly selected (N-70, N-128, N-165).

To obtain maximum efficiency, it is essential that not only a consistent and uninterrupted separation be provided between floating floor and structural slab but, at the same time, any contact between floating floor and surrounding walls be also avoided (N-165). The selection of appropriate materials for a floating floor, its workmanlike detailing and specification, is a delicate problem in architectural acoustics.

Figure N.7 shows details of floating concrete and wood floors.

Additional data on floating floors is available from various sources (N-170, N-175, N-180, N-194, N-195).

Suspended ceilings attached to the structural floor will contribute substantially to the sound insulating quality of a floor, against both air-borne and impact noises, if they possess the following characteristics (M-122, N-70, N-165):

(a) the ceiling membrane weighs not less than 5 lb/ft^2. If an absorbent blanket (mineral or glass wool) is used in the air space above the ceiling, the weight of the ceiling membrane can be reduced;

(b) the ceiling membrane is not too rigid;

(c) direct paths of noise transmission through the ceiling membrane are avoided by the use of a solid and air-tight membrane;

(d) gaps between ceiling and surrounding structure are sealed, thus avoiding noise penetration through direct air paths;

(e) the number of points of suspension from structural floor above are reduced to a minimum; the use of resilient hangers is preferred to rigid ones;

(f) air space between ceiling membrane and structural floor is increased to a reasonable maximum.

Walls built only up to ceiling height suffer a serious reduction in their TL; it is, therefore, essential that the space between a suspended ceiling and structural soffit, above the line of the partition wall, be adequately sealed.

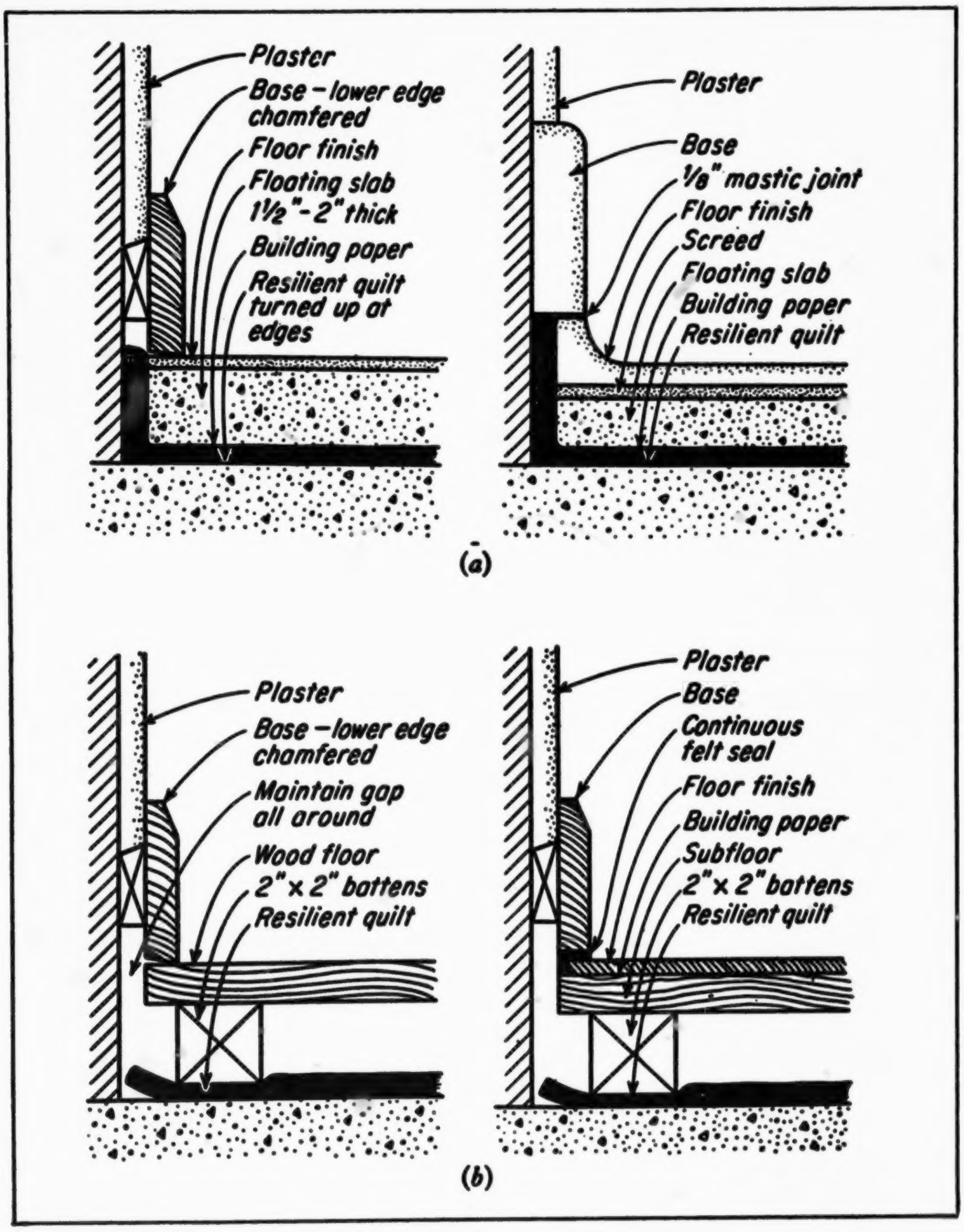
Plaster
Base - lower edge chamfered
Floor finish
Floating slab 1½"-2" thick
Building paper
Resilient quilt turned up at edges
Plaster
Base
⅛" mastic joint
Floor finish
Screed
Floating slab
Building paper
Resilient quilt
(a)
Plaster
Base - lower edge chamfered
Maintain gap all around
Wood floor
2" x 2" battens
Resilient quilt
Plaster
Base
Continuous felt seal
Floor finish
Building paper
Subfloor
2" x 2" battens
Resilient quilt
(b)

Figure N.7. Details of floating concrete floors (a), and floating wood floors (b). (Reprinted from The Transmission and Radiation of Acoustic Waves by Solid Structures, contained in "Noise Reduction" by L.L. Beranek, McGraw-Hill Book Co., New York, 1960).

Manufacturers of various suspended ceiling assemblies seem insufficiently concerned at the serious reduction in the TL of a wall built up to a suspended ceiling. This is understandable because any objection against the reduced acoustical performance of a suspended ceiling would undermine the manufacturers' claims for complete flexibility and demountability (N-150).

The annual bulletin of the Acoustical Materials Association (New York) lists attenuation factors ("AF") of many commercial suspended ceiling assemblies at representative frequencies (E-12). These values represent differences, in decibels, between the sound level in the source room and the sound level in the receiving room, provided that (a) the sound is transmitted via the plenum above the ceiling, and (b) the partition between source room and receiving room extends only to the ceiling. Where noise transmission between rooms is likely to occur essentially through the ceiling-plenum path, a formula is given in the bulletin for the noise reduction (NR) between the rooms. A more precise treatment is as follows:

$$NR_{ceiling} = AF+10 \log_{10}\frac{A_2}{S_p} - 6 \text{ db}$$

where AF is the attenuation factor for given acoustical ceiling assemblies at representative frequencies,

A_2 is the total acoustical absorption, in ft^2 units, in the receiving room (described in subsection D.5), and

S_p is the area of the plenum opening over the partition, in ft^2 units.

At present the attenuation factors are given for each frequency, rather than in terms of a single average or rating number. For purpose of comparison with partition ratings which are commonly given in terms of the Sound Transmission Class, the single attenuation factor for 350 cps is found to be a useful index (S-123).

This formula is naturally applicable only where the same ceiling assembly is used in both source room and receiving room.

The noise reduction via the ceiling-plenum path can be compared with that taking place directly through the dividing partition between source room and receiving room (discussed in paragraph N.1.6); this comparison will reveal the path that is primarily responsible for the transmission of noise.

It is an interesting acoustical phenomenon that it is rather difficult to detect the harmful noise transmission through a suspended ceiling (N-4). This is due to the so-called Haas effect (F-22, M-18) which states that if the same speech sound is picked up from two directions, the sound that arrives first determines the apparent direction. In the present case, if speech sound can travel simultaneously through the partition and through the suspended ceiling, then the partition will offer the shorter path for the sound. It will therefore appear as if the sound is coming through the partition, creating the false illusion that the partition and not the suspended ceiling is the noise transmitter.

The following Table N.3 lists average air-borne transmission losses of typical floor constructions (M-122).

Table N.3. Average TL of typical floor constructions for air-borne noises. (Reprinted from Noise Transmission in Buildings by T.D. Northwood, Canadian Building Digest, Division of Building Research, National Research Council, Ottawa, Oct. 1960.)

	Impact rating dB
A. Air-borne transmission loss 50 dB or more.	
1. 4" solid concrete or equivalent slab weighing at least 50 lb/ft^2; ceiling side bare or plastered directly on slab; floor side wood sleepers, rough and finish floors.	30
2. As in (1) except floor side 1" foamed plastic or paper-covered glass fibre quilt, supporting 2" concrete.	30
3. As in (1) except floor side parquet or linoleum; ceiling side wood furring, ½" gypsum lath, ½" sanded gypsum plaster.	5●
4. As in (3) but ceiling side ½" gypsum lath suspended on resilient clips, ½" sanded gypsum plaster.	20
5. As in (3) but ceiling mounted on separate joists supported at walls.	25
6. Open steel joists or similar structure; on floor side form-work, paper-covered glass fibre quilt or foamed plastic, 2" concrete; ceiling side ½" gypsum lath on resilient clips, ½" sanded gypsum plaster.	30
B. Air-borne transmission loss 45-49 dB.	
1. 4" solid concrete or equivalent slab construction weighing 50 lb/ft^2.	2●
2. As above but floor side finished in linoleum or wood parquet.	5●
3. As in (1) but floor side finished with carpet and underlay.	10●

● Impact rating not adequate for separating dwelling units.

Additional published information on various floor and ceiling constructions is available from many sources (N-1, N-3, N-4, N-5, N-6, N-20, N-28, N-32, N-35, N-53, N-59, N-61, N-66, N-70, N-77, N-85, N-120, N-128, N-130, N-137, N-138, N-143, N-156, N-157, N-158, N-159, N-160, N-163, N-164, N-165, N-166, N-168, N-169, N-172, N-173, N-174, N-176, N-180, N-182, N-183, N-184, N-186, N-187, N-188, N-190, N-191, N-192, N-198, N-199, N-200, N-201, N-204, N-206, S-35, GB-3, GB-6, GB-9, GB-19, GB-20, GB-21, GB-25, GB-27, GB-28, GB-29, GB-52, GB-61, GB-62).

N.3.3 Doors

Doors always constitute acoustically weak elements of walls. This is due to the facts that (a) their surface weight is normally less than that of the wall into which they are built, and (b) the gaps around their edges, unless sealed, offer an easy passage for the transmission of noise (M-6, M-18, N-32).

Sound insulating doors should be of solid and heavy rather than hollow and light construction, with their edges well sealed all around. Rubber, foam-rubber or foamed plastic strips, adjustable or self-aligning stops and gaskets can be used for sealing the edges of doors; they should be installed so that they are slightly compressed between door and stop when the door is in closed position. Bottom edges can have a replaceable strip of felt or foam-rubber stuck to them to minimize the gap between door and floor. An improved alternative is to install drop-bar type draught excluders or threshold closers (often supplied with integral kick-plates).

If doors have to possess an unusually high degree of sound insulation they are built so that a separation between opposite faces of the door is carried through uninterruptedly from edge to edge, in both directions (N-208, N-209, N-218).

In the acoustical evaluation of a sound insulating door, distinction should be made between the panel value and the operating value of its TL rating. Panel values are obtained when the door is tested with hermetically sealed edges; operating values (always lower than the panel values) obtained from tests under conditions simulating field installation in every respect, reflect a more realistic acoustical performance.

The flexible utilization of contemporary architectural spaces often requires the use of movable partitions (or operating partitions) which are, in fact, giant size folding, sliding or side coiling doors with easily operated, structurally integrated and carefully sealed - more or less - sound proof panels (N-189, N-210, N-211, N-215).

N.3.4 Windows

Similar to doors, windows also constitute acoustically weak components of their surrounding enclosures. This happens because (a) their surface weight is much below that of the surrounding enclosure, and (b) their connection with the wall, unless adequately sealed, constitutes direct paths for the penetration of exterior noise, particularly where standard windows are used (N-110, N-207, N-212, N-213, N-216, N-218, N-219).

The TL of windows will depend on the number, thickness and relative position of the panes, and on their edge connection to the wall. Double glazing with well sealed edges are basic features of sound insulating windows.

The sound insulating quality of open windows practically equals zero.

If a high degree of sound insulation is expected from a window, double- or triple-pane construction is preferable to very thick but single pane. The distance between the panes has a distinct effect on the TL of the window, particularly at low frequencies; the TL improves with increasing distance between the panes. This is illustrated in Figure N.8, which shows the TL of two 1/8" thick panes as a function of the separation between the panes, at 250 and 1000 cps frequencies; it is assumed that the edges of the panes are perfectly sealed (N-214). Under these particular conditions the mass law is no longer applicable.

In air-conditioned buildings the TL of fixed windows, with thick and double panes well spaced and structurally isolated from each other, may approximate that of the surrounding wall.

The addition of sound absorbing treatment to the window reveal between the panes, the mounting of panes in an elastic material (cork, felt, sponge, rubber, Neoprene, etc.), and elimination of parallelism between panes, will result in a considerable increase in the TL of windows (N-32, N-214). These methods of increasing the sound insulating quality of windows are utilized for control and observation windows used in Radio, Television, Recording Studios, etc.

Various sound retarding windows, manufactured mainly for thermal insulating purposes, are available on the market (Twindow, Thermopane, etc.). Special sound insulating glasses are manufactured lately of 2 to 4 thin layers of sheet or polished plate glass laminated into a single panel with soft, transparent plastic interlayers. These special panes successfully combine the two physical characteristics of an acoustically efficient sound insulating barrier: mass and limpness. These panes are available in 9/32", 7/16" and 5/8" thicknesses, called Acousta-Pane II, III, and IV, respectively, denoting the number of glass sheets laminated into the single panel. Their transmission losses are shown in Figure N.9.

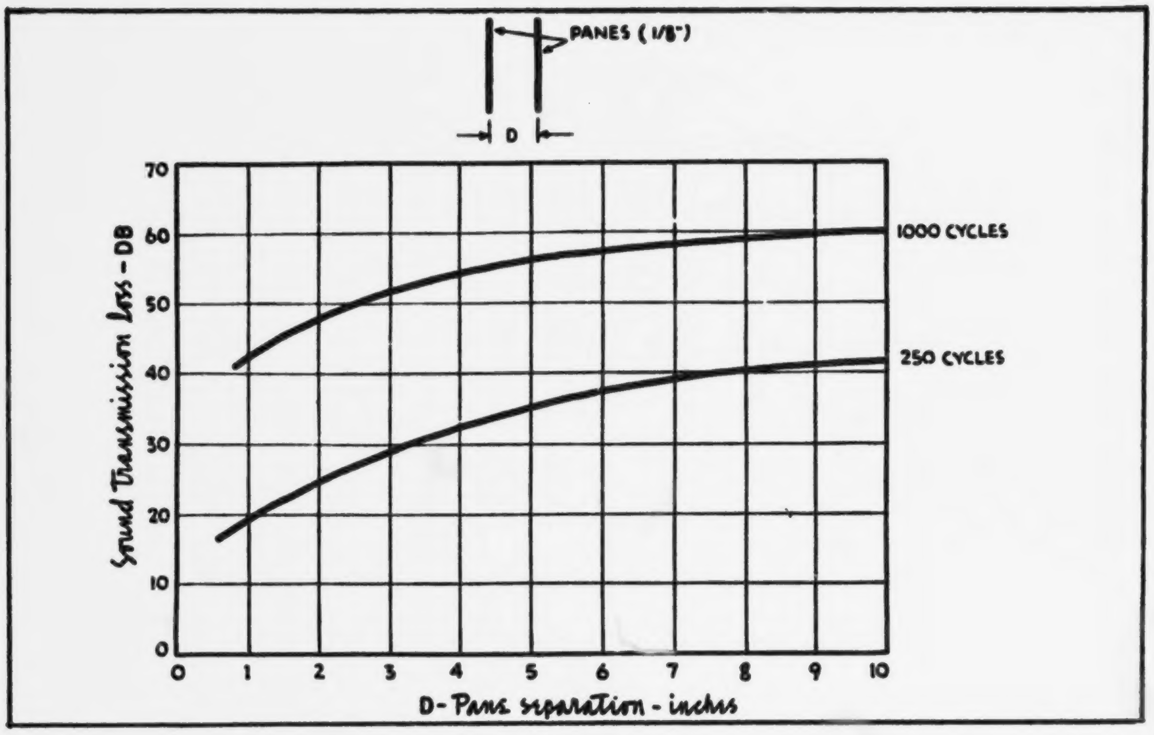

Figure N.8. Transmission loss of two 1/8" thick panes as a function of the separation between them, at 250 and 1000 cps frequencies, with perfectly sealed edges. (Reprinted from Progr. Arch., Mar. 1960).

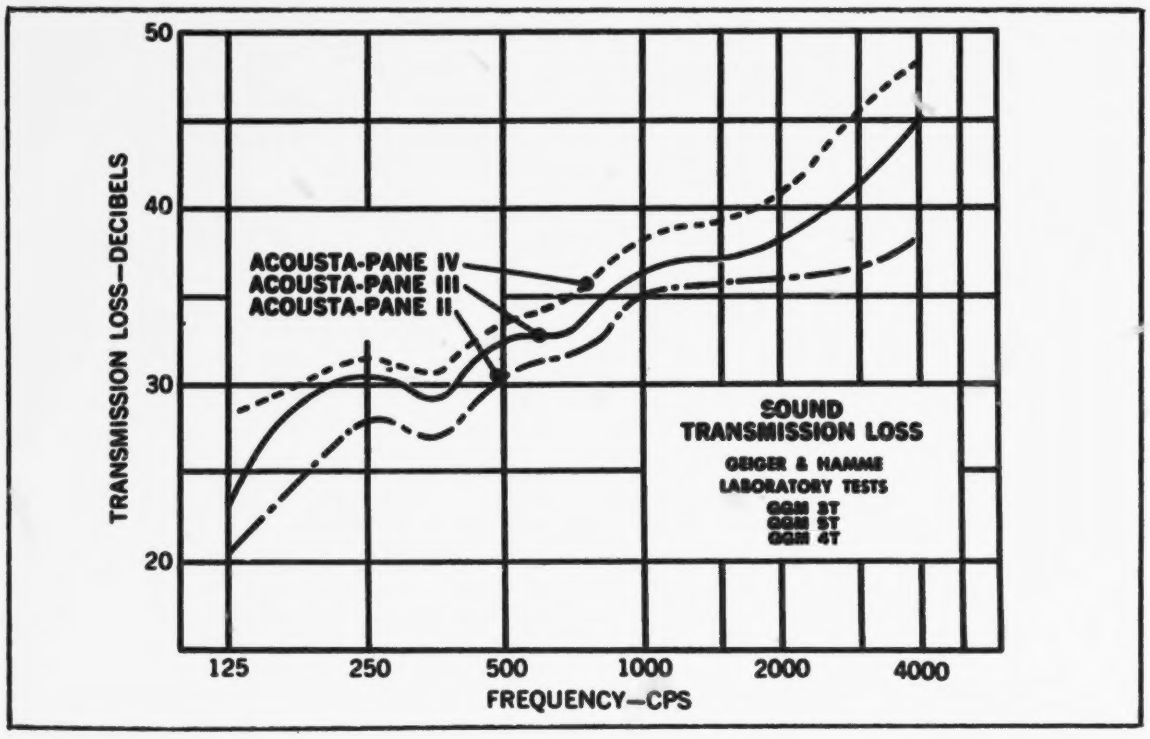

Figure N.9. Transmission losses of 2-ply, 3-ply, and 4-ply sound insulating glass panels, called Acousta-Pane II, III, and IV, respectively. (Reprinted from a booklet published by the Amerada Glass Corporation, Chicago, Ill., 1963).

N.3.5 Discontinuous construction

If a particularly high degree of insulation is required for a room or for part of a building against air-borne noises, structure-borne noises and vibrations, all the measures discussed so far in this Section have to be incorporated into a single design, called discontinuous construction, or "box within a shell". Basic elements of such an arrangement are shown diagrammatically in Figure N.10 (N-128). The room illustrated in this Figure could be used for audiometric tests, as a Radio or Recording Studio, or for any other purpose where an extraordinary degree of acoustical privacy has to be achieved (M-6, N-27, N-128, GB-52). The room illustrated is accessible through a sound lock; it has a floating floor on top of the structural slab, the walls are built on the floating floor separated from the load-carrying exterior walls, and the ceiling is resiliently suspended from the structural floor above. The acoustical separation of the inner shell from the building structure must not be short-circuited by rigid, connecting links; such as,wall ties, ducts, pipes, unisolated windows, etc.

A practical application of the discontinuous construction is shown in Figure N.11;it outlines a typical section of a discontinuous construction, with floating floor, isolated wall and resiliently suspended ceiling. Various discontinuous constructions have been presented in numerous publications (J-1, J-3, J-4, J-17, J-23, J-90, S-87, S-89, S-102, S-104, S-105, S-109, S-110, GB-52).

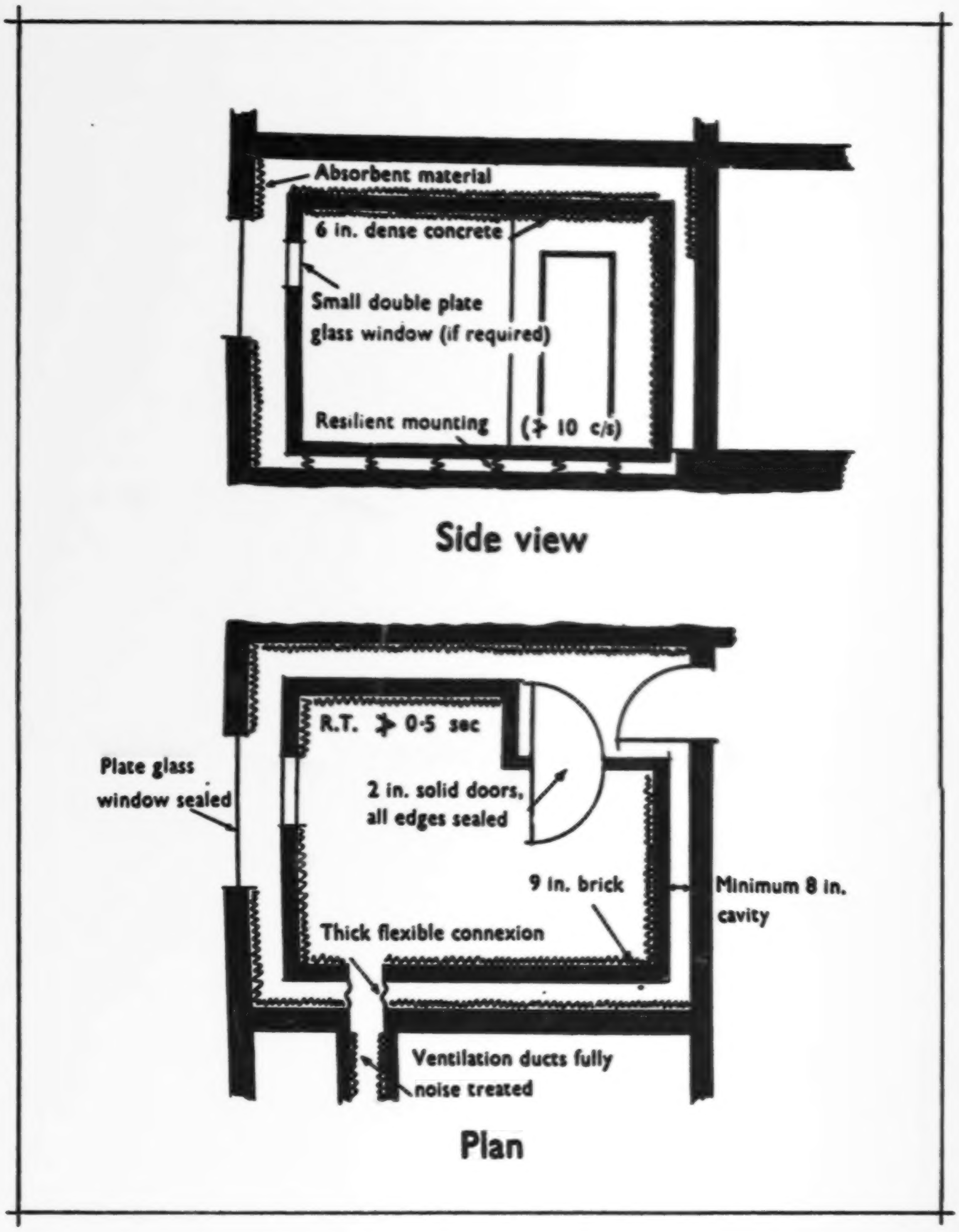
Absorbent material
6 in. dense concrete
Small double plate glass window (if required)
Resilient mounting
(≯ 10 c/s)
Side view
R.T. ≯ 0·5 sec
Plate glass window sealed
2 in. solid doors, all edges sealed
9 in. brick
Minimum 8 in. cavity
Thick flexible connexion
Ventilation ducts fully noise treated
Plan

Figure N.10. Diagrammatic illustration of a discontinuous construction. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

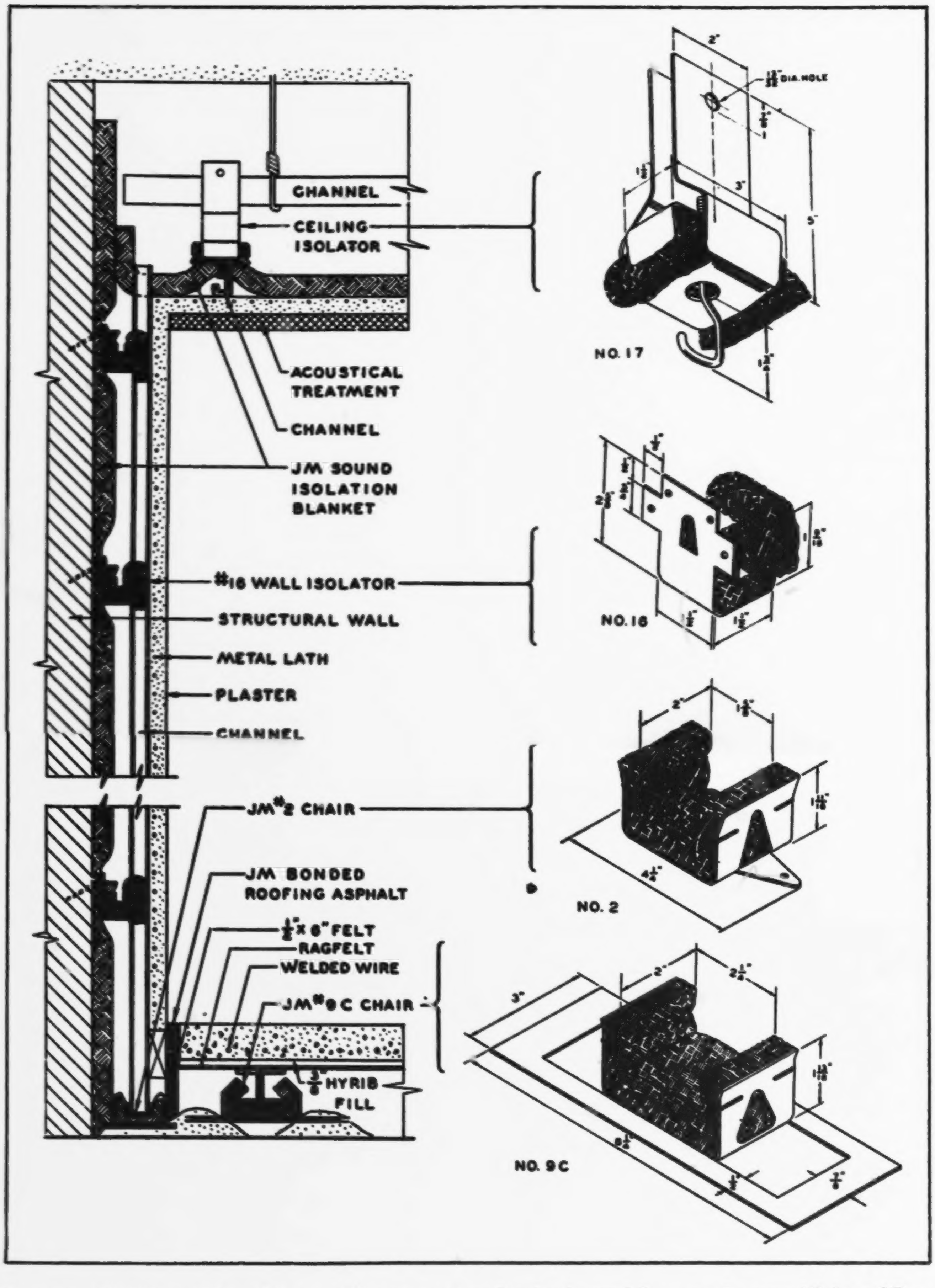
CHANNEL
CEILING ISOLATOR
ACOUSTICAL TREATMENT
CHANNEL
JM SOUND ISOLATION BLANKET
#16 WALL ISOLATOR
STRUCTURAL WALL
METAL LATH
PLASTER
CHANNEL
JM#2 CHAIR
JM BONDED ROOFING ASPHALT
½"x 6" FELT
RAGFELT
WELDED WIRE
JM#9C CHAIR
⅜" HYRIB
FILL
DIA. HOLE
NO. 17
NO. 16
NO. 2
NO. 9C

Figure N.11. Floating floor, isolated wall, and resiliently suspended ceiling used in discontinuous construction. (Reprinted from Sound Control by Canadian Johns-Manville Co., Toronto).

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(See list of abbreviations on page 1)

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Section O. Control of Mechanical Noises

O.1 Control of noise due to plumbing systems

O.2 Control of noise in ventilating (and air-conditioning) systems

- O.2.1 Acceptable noise levels
- O.2.2 Noise sources
- O.2.3 Noise reducing components
- O.2.4 Determination of attenuation required

O.3 Control of machinery noise

References

Contemporary mechanical equipment and machinery render the lives of the occupants of buildings more comfortable, more enjoyable and more productive; however, this equipment and machinery are fundamental contributors to noisy buildings.

In the control of mechanical noise the complete elimination of the noise is very seldom, if ever, the objective; technically this would be extremely difficult, uneconomical,and also unnecessary (0-39). The general objective is rather to produce a balanced noise environment which means the attenuation of noise to a permissible level, depending on various conditions; such as, anticipated activity in the room, the required degree of privacy, etc. (0-86). Excessive noise reduction is often detrimental because this will reduce acoustical isolation of one occupancy from another (paragraph M.6.10).

Mechanical noises can be created (a) by plumbing systems, (b) by ventilating and air-conditioning systems, and (c) by machinery.

0.1 Control of noise due to plumbing systems

Flow-control devices (valves) and toilets constitute serious sources of plumbing noise (0-17, 0-44, 0-73, 0-90). In addition, a great amount of noise in plumbing systems is due to turbulent flow (0-66, 0-73). The noise created by turbulent flow will be increased, in certain cases, due to a phenomenon called cavitation (0-17, 0-44). The noise produced at these sources will be transmitted along the pipe as well as through the water in the pipe.

As in so many cases of noise control,the best procedure is to suppress the noise at the source, e.g., by selecting and installing quietly operating fixtures. If this is not possible, then as a next step an attempt must be made to prevent the penetration of noise into the water pipe or to prevent its transmission from the pipes to the building structure (0-17). Transmission along the pipe can be reduced considerably by inserting a flexible (rubber, rubber-and-fabric, plastic, etc.) pipe between the source and the metal pipe.

If noise is transmitted through a pipe, then the amount of noise that is radiated by the pipe itself is negligible (0-17, 0-44); the disturbing sound is radiated by the building structure (partitions, slabs, ceilings, etc.) to which the pipe is fixed. To eliminate this noise radiation, pipes should be resiliently mounted, i.e., adequately insulated from their supports by wrapping them in felt, asbestos or other suitable insulating material (0-17, GB-21, GB-43). If the noise-reducing measures recommended above cannot be exploited to the required extent, the noise-conducting pipes should be screened from the affected rooms by building them into suitable ducts or shafts. One must ensure that these pipe ducts or shafts do not conduct other airborne noises from one part of the building to others (GB-43).

Waste water flowing in pipes can also produce embarrassing, although never too loud, noises. These noises can be reduced to the required level by placing the sewage pipes in ducts with proper isolation between pipes and duct enclosures (GB-43).

The principles for noise reduction of water systems are also applicable to steam and gas lines (0-44).

Additional recommendations for the elimination of plumbing noises have been discussed in paragraph M.6.6.

0.2 Control of noise in ventilating (and air-conditioning) systems

0.2.1 Acceptable noise levels

In rooms where listening to speech or music is important, the noise level created by a ventilating (or air-conditioning) system must be about a few dB below the desired level of background noise. This is necessary in order to avoid interference of ventilation noise with the intelligibility of speech or with the enjoyment of music (0-18, 0-36, 0-45).

In certain rooms, on the other hand, such as Offices, Hospital Rooms, Restaurants, etc., the aim in the control of ventilation noise is not to eliminate all the noise caused by the system,but to create a balanced sonic environment. The noise should be reduced only to a degree necessary to allow the anticipated activity in the room at a comfortable level (0-18, 0-86). The quieting of ventilation noise below this level would be wasteful. In addition, as mentioned before, excessive noise reduction would remove that artificial masking noise which can beneficially "cover up" and render inaudible or unintelligible intruding weaker sounds. Noise control with masking noise has been outlined in paragraph M.6.10 (0-74).

The control of ventilation noise should start, therefore, with the critical determination of criteria for the desired background noise levels in each room, depending on the activities to be carried on in each particular rooms (R-4, R-6, R-11, R-13, R-15, R-22, S-15). Criteria for noise in various spaces are discussed and listed in Section R.

Figure 0.1 illustrates a typical ventilating system reduced to its essential components (0-45).

0.2.2 Noise sources

Noises encountered in ventilating systems can be grouped as follows (0-14, 0-18, 0-33, 0-34, 0-56, 0-62, 0-63, 0-74, 0-86, 0-95, 0-96, 0-100, 0-101):

(a) mechanical equipment noise caused by fans, motors, etc., and transmitted (1) through and along ducts or enclosures (walls, ceilings, etc.) as air-borne noise,

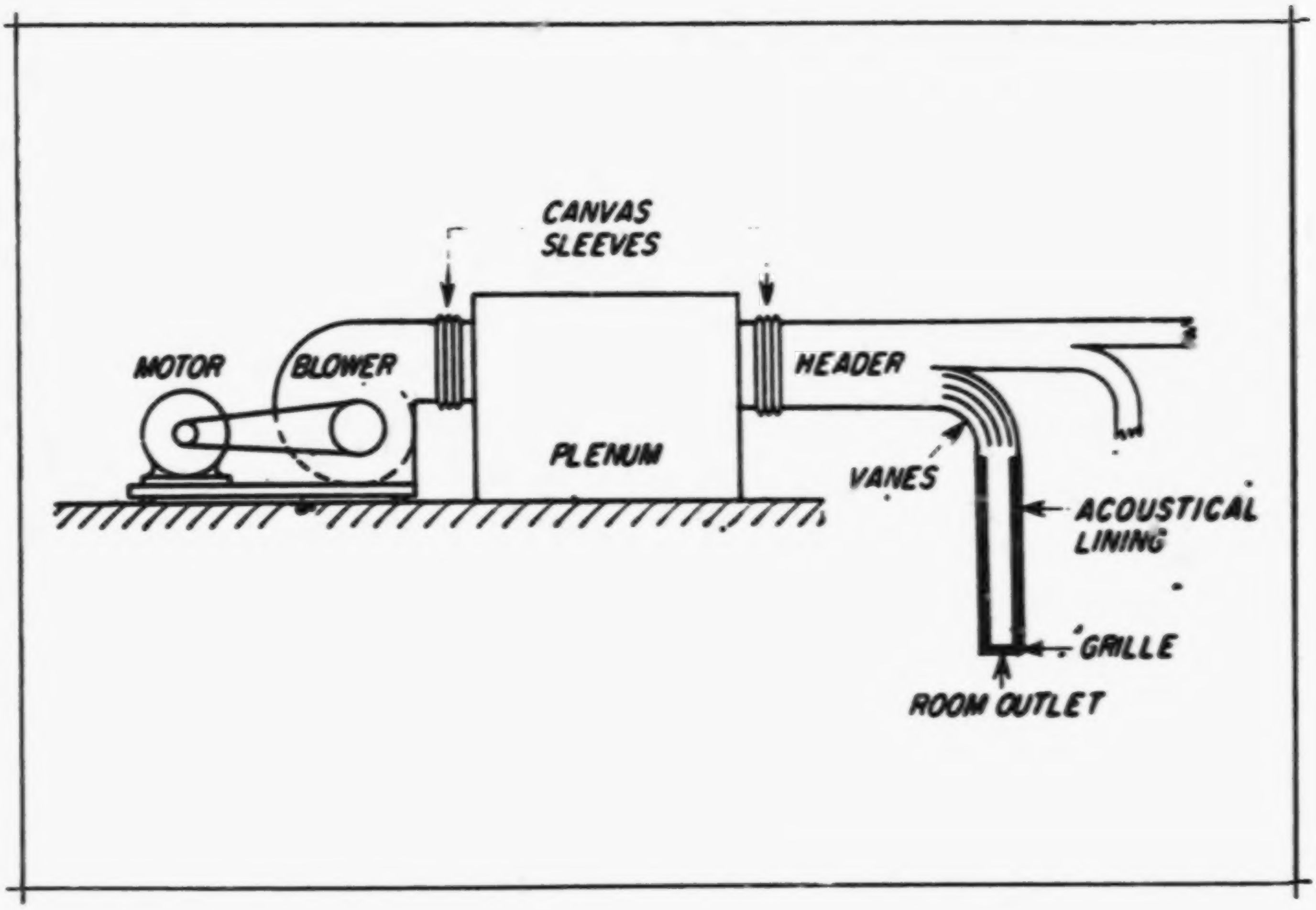
CANVAS SLEEVES
MOTOR
BLOWER
HEADER
PLENUM
VANES
ACOUSTICAL LINING
GRILLE
ROOM OUTLET

Figure 0.1. Typical ventilating system reduced to its essential components. (Reprinted from Heating and Ventilating System Noise, contained in "Handbook of Noise Control", by R.W. Leonard, McGraw-Hill Book Co., New York, 1957).

or (2) through the building structure or duct walls as structure-borne noise or vibration;

(b) "self-noise" from air motion and turbulence within the distribution system created by grilles, diffusers, dampers, pressure regulators, etc., and transmitted through or along ducts;

(c) cross-talk from one space to another, e.g., speech that enters a supply or return air grille in one room, travels through the duct or plenum, and emerges in a nearby room through another ventilating grille; and

(d) noise transmitted from sources external to the building.

Figure 0.2 illustrates the various noise sources, the several paths, and receivers, all interconnected and interrelated in a ventilating system (0-86). Figure 0.3 shows how outdoor noises can penetrate a ventilating system through an exposed portion of the duct (0-62).

A detailed description and evaluation of the various noise sources of ventilating systems has been presented in numerous articles (0-10, 0-14, 0-16, 0-17, 0-18, 0-19, 0-20, 0-24, 0-25, 0-28, 0-30, 0-32, 0-33, 0-35, 0-36, 0-38, 0-40, 0-41, 0-43, 0-45, 0-48, 0-50, 0-51, 0-53, 0-54, 0-56, 0-57, 0-61, 0-62, 0-63, 0-67, 0-68, 0-70, 0-73, 0-74, 0-75, 0-76, 0-77, 0-79, 0-84, 0-86, 0-94, 0-95, 0-96, 0-97, 0-98).

0.2.3 Noise reducing components

In the control of ventilating noise the suitable selection and the workmanlike installation of the system components are prerequisites to the attenuation of noise; there are, however, additional ways in which the noise will be reduced between the source and the recipients, as follows (0-14, 0-18, 0-36, 0-56, 0-62, 0-63, 0-74, 0-86):

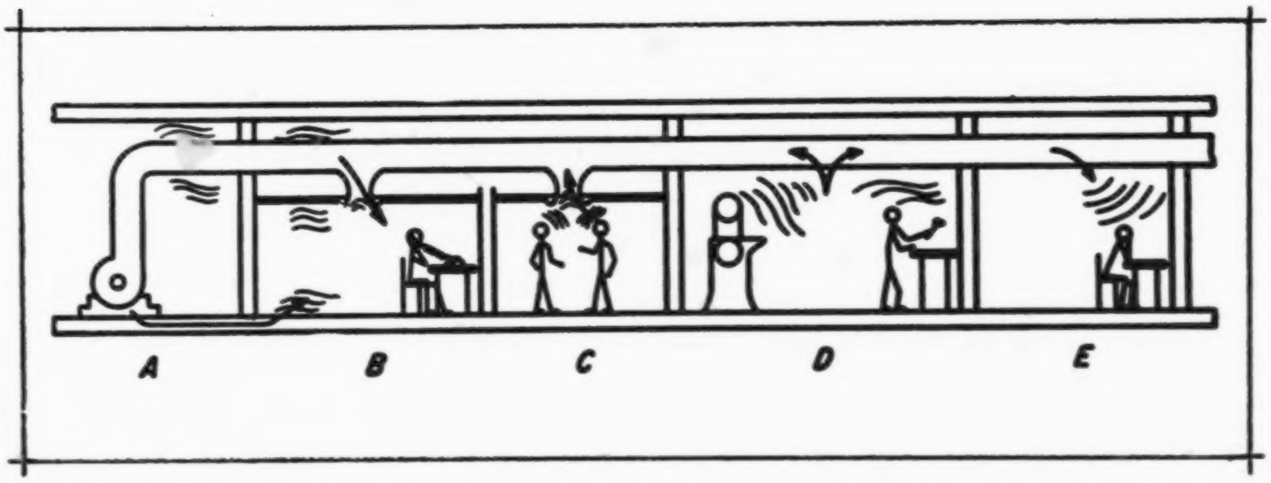

Figure 0.2. Various noise sources, paths, and receivers interconnected in a ventilating system. Vibrations produced in Fan Room "A" may enter room "B" through the structural floor. Noise created by the fan may enter room "B" and all other rooms through the air diffusers or by vibration of the duct walls. Speech originating in room "C" may produce noise in room "B" (cross talk). Noise from Shop "D" may travel through the ducts to rooms "B", "C", and "E". (Reprinted from Noise Control in Ventilation Systems, contained in "Noise Reduction", by C.H. Allen, McGraw-Hill Book Co., New York, 1960).

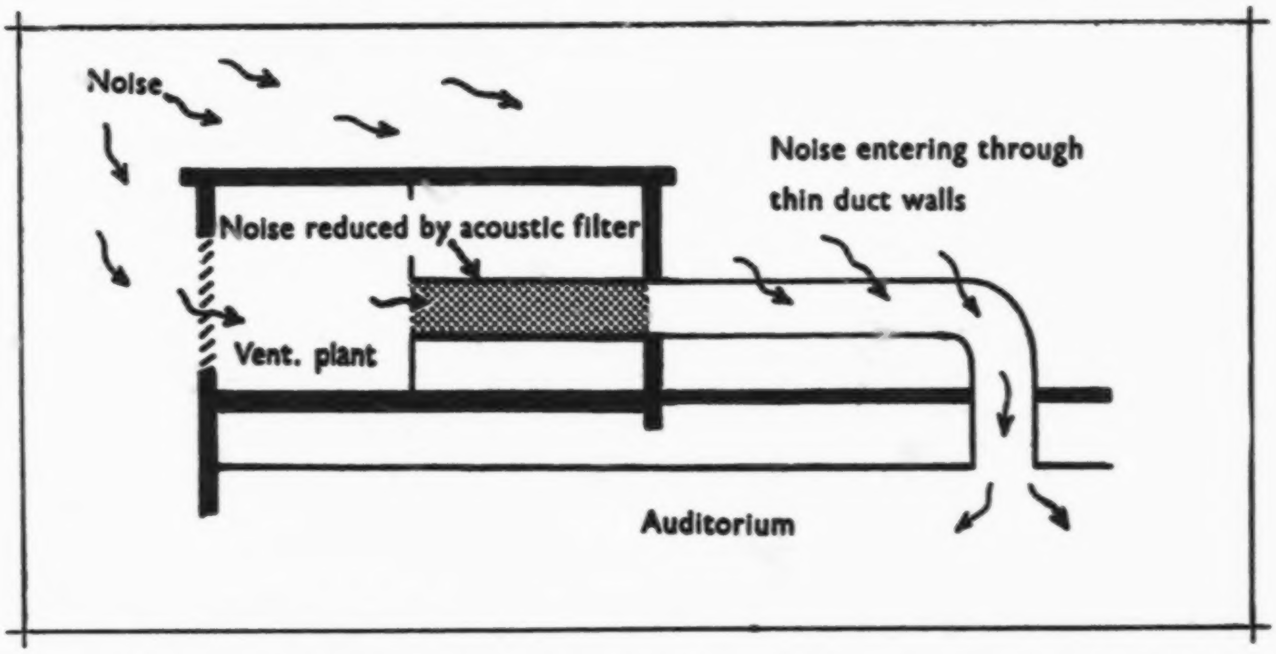
Noise
Noise entering through thin duct walls
Noise reduced by acoustic filter
Vent. plant
Auditorium

Figure 0.3. Outdoor noises can "short-circuit" sound insulation measures through exposed, thin duct walls. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

(a) dissipation of noise due to transmission through duct walls into spaces outside the ducts;
(b) absorption of noise in duct wall linings;
(c) reduction of noise due to bends;
(d) division of noise into several branches;
(e) reflection of noise back towards the source;
(f) spreading of noise into the room at supply or return air grilles;
(g) absorption of noise in the room itself where the duct ended.

If thermal insulation is installed along the outside surface of the duct walls, this will contribute,to a certain degree, to the TL of the duct walls (0-36, 0-86).

Sound absorbing materials, such as glass-fiber or mineral-fiber boards, installed along the inside of rectangular or round ducts, will increase the attenuation of noise along the duct. Sound absorbing materials used for duct lining should possess the following properties: (a) high absorption coefficient, (b) smooth surface for low air friction, (c) adequate strength to resist disintegration due to air flow, and (d) adequate resistance against fire, rot, vermin and odour (0-6, 0-15, 0-52).

A large expanded section of a duct (called plenum chamber) lined with sound absorbing material will contribute to the reduction of noise within the duct. Plenum chambers are used when a large number of smaller ducts are fed by one main supply fan (0-45, 0-86).

Ducts with small cross sections are more effective noise attenuators than those with larger cross sections; therefore, when a duct is too short to provide satisfactory reduction of noise, added attenuation can be obtained, at the expense of increased pressure drop, (a) by dividing the duct into a number of smaller lined ducts (egg-crate type sound absorbing cells, splitters, etc.), or (b) by using prefabricated (package) attenuator units, called silencers (0-14, 0-22, 0-45, 0-81, 0-86, 0-87, 0-88).

Methods for calculating the attenuation in lined ducts are published in various articles and in manufacturers' catalogues (0-2, 0-3, 0-5, 0-7, 0-8, 0-9, 0-11, 0-14, 0-23, 0-27, 0-36, 0-45, 0-58, 0-59, 0-64, 0-81, 0-86, 0-87, 0-92, 0-99, GB-54).

When a duct divides into branches, the noise traveling through the main duct will divide approximately in proportion to the areas of the branches (0-86).

Reflection of noise happens when an abrupt change takes place in the cross-sectional area of the duct.

The noise level close to the duct exit is greater than at some distance from the grille, therefore, in rooms used for listening, the duct opening should be as far as possible from the listeners (GB-43).

0.2.4 Determination of attenuation required

In the control of ventilation noise the fundamental problem is to determine the attenuation that is necessary to secure the desired amount of background noise in the spaces to be ventilated (or air-conditioned). To achieve this, the following have to be ascertained (0-14, 0-35, 0-36, 0-74, 0-86, 0-94):

(a) the Noise Criteria for each room to be ventilated (or air-conditioned); this is discussed in subsections R.2 and R.3;

(b) the amount of noise produced by each noise source;

(c) the attenuation of noise provided by ducts, walls, ceilings, etc., between each source and the room in question;

(d) the noise levels at the recipients' positions in that room;

(e) the required additional attenuation given by item (d) minus item (a).

Once the required attenuation has been determined, then a decision has to be made as to whether

(a) the noise can be reduced at the source (e.g., at the fan), or

(b) noise reduction devices (lining, silencer, etc.) should be used, usually close to the critical area.

It must be stressed again that a most effective and economical mean of the control of ventilation noise is achieved by concentrating and locating the noise-producing equipment (a) as far as possible from the rooms requiring a high degree of quiet, and (b) in a part of the building where noise and vibration can be relatively well tolerated (0-62).

In the selection of the most suitable procedure for the control of ventilation noise, it is recommended that an approach be adopted that will allow the acoustical consultant to cooperate most efficiently with the architect and mechanical engineer during successive design stages (0-86).

0.3 Control of machinery noise

Heating chambers (boilers), Diesel generators, pumps, compressors, cooling towers, motors, pneumatic devices, etc., are notorious sources of machinery noise. Normally such machinery is placed in the basement of buildings (0-37, 0-42, 0-46, 0-47, 0-62), although in high rise buildings it is sometimes imperative that the mechanical-equipment floor be located on top of the building or somewhere between the typical floors (S-15).

The required degree of noise control will depend on the noise level produced by the machinery and that which can be tolerated in the room under consideration.

In order to provide adequate noise reduction between mechanical-equipment rooms and adjoining occupancies, the following noise paths will have to be checked (S-15):

(a) air-borne noise paths between the noisy Equipment Room and the adjoining or nearby occupancies through walls, floors, ceilings, etc.;

(b) structure-borne noise paths between vibrating equipment and adjoining areas; and

(c) duct-borne paths for the transmission of fan noise and airflow noise into those adjacent rooms serviced by the ventilating or air-conditioning equipment.

To secure the required background noise levels in the rooms close to an Equipment Room, the following measures should be considered (S-15):

(a) the installation of a floating floor for the entire Equipment Room area;

(b) the installation of the individual articles of equipment and machinery on the floating slab with vibration-isolating mounts, such as, steel springs, rubber-in-shear mounts, cork, felt, etc. (discussed in subsection P.3);

(c) the provision for a resiliently suspended impervious dense ceiling in the rooms below the machinery floor, as shown in Figure O.4 (S-15); and

(d) control of duct-borne fan noise and air-flow noise. This was discussed in subsection O.2.

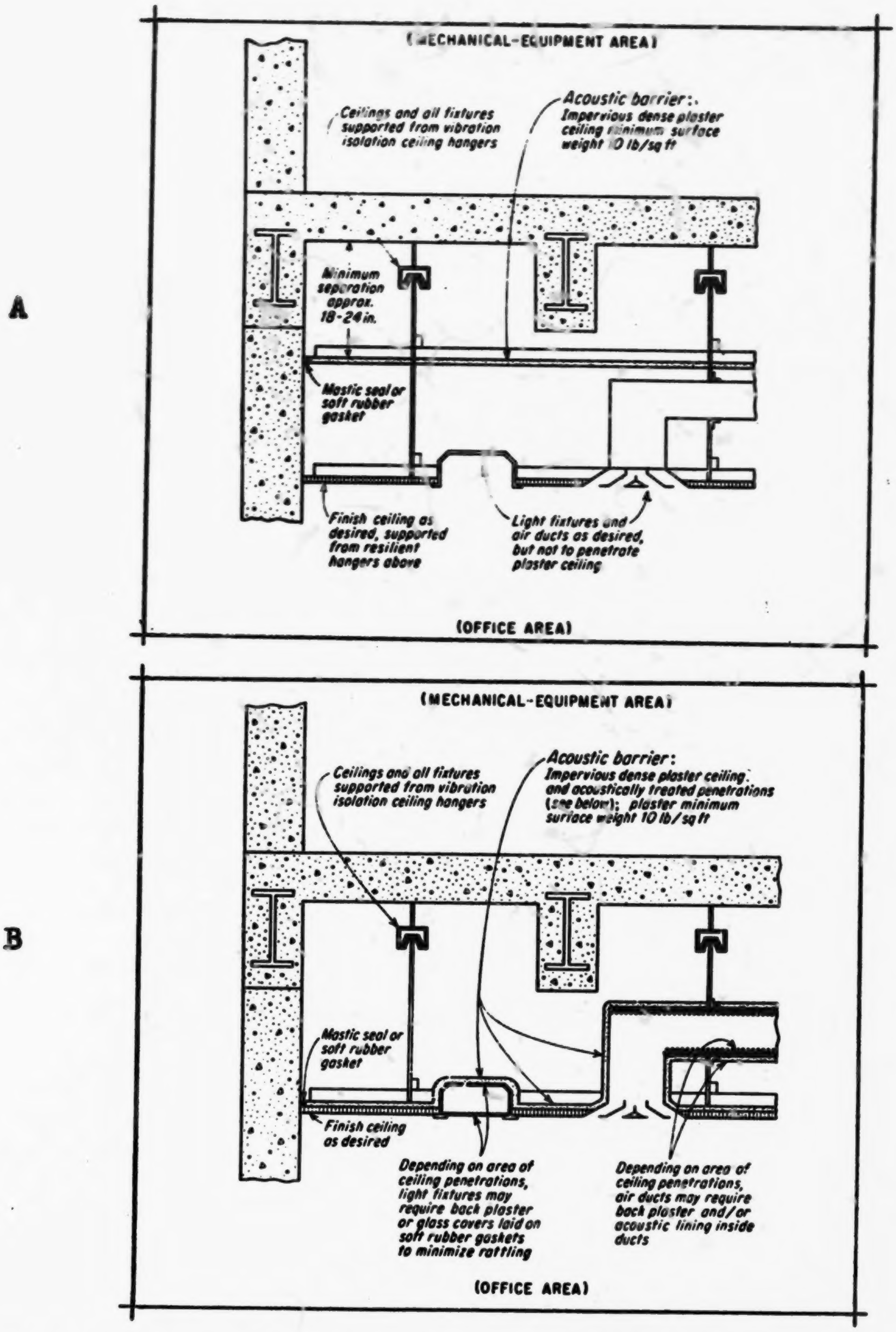
A
(MECHANICAL-EQUIPMENT AREA)
Ceilings and all fixtures supported from vibration isolation ceiling hangers
Acoustic barrier: Impervious dense plaster ceiling minimum surface weight 10 lb/sq ft
Minimum separation approx. 18-24 in.
Mastic seal or soft rubber gasket
Finish ceiling as desired, supported from resilient hangers above
Light fixtures and air ducts as desired, but not to penetrate plaster ceiling
(OFFICE AREA)
B
(MECHANICAL-EQUIPMENT AREA)
Ceilings and all fixtures supported from vibration isolation ceiling hangers
Acoustic barrier: Impervious dense plaster ceiling and acoustically treated penetrations (see below); plaster minimum surface weight 10 lb/sq ft
Mastic seal or soft rubber gasket
Finish ceiling as desired
Depending on area of ceiling penetrations, light fixtures may require back plaster or glass covers laid on soft rubber gaskets to minimize rattling
Depending on area of ceiling penetrations, air ducts may require back plaster and/or acoustic lining inside ducts
(OFFICE AREA)

Figure 0.4. Diagrammatic layout of a resiliently suspended impervious dense ceiling beneath a noisy mechanical-equipment area. A: acoustic barrier separated from finish ceiling. B: acoustic barrier combined with finish ceiling. (Reprinted from Case Histories of Noise Control in Office Buildings and Homes, contained in "Noise Reduction", by L.N. Miller, McGraw-Hill Book Co., New York, 1960).

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relative to Section O: "Control of Mechanical Noises"
(See list of abbreviations on page 1)

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Section P. Vibration Control

P.1 Effects of vibration
P.2 Types of application
P.3 Materials for vibration control
References

Vibration means the movement of a structure (or any other solid body) caused by some alternating force, e.g., an out-of-balance rotating part of a machine. Vibration may be transmitted readily to distant parts of the structure to which the vibrating machine is fixed, and re-radiated from large surfaces (walls, ceilings, windows) as annoying noise; it may be transmitted even to other nearby buildings (P-1, P-4, P-7, P-8, P-9, P-12, P-16, P-20, P-28, GB-43).

P.1 Effects of vibration

Vibration may have the following effects (P-7, P-30, P-36, GB-43):

(a) it may cause damage to buildings;
(b) it may be annoying to the occupants;
(c) it may interfere with work and harm precision instruments; and
(d) it may cause noise if the rate of vibration is within the audio-frequency range.

The transmission of vibration from one structure to another will be avoided by interposing a relatively flexible element between the two structures; this flexible element or elastic device is called a "vibration isolator" or "resilient mount" (P-2, P-12). The use of vibration isolators is illustrated in Figure P.1 (N-6).

P.2 Types of application

There are two types of application of vibration isolation (P-3, P-12, P-36):

(a) Active isolation, in which the transmission of unbalanced forces from a machine to its foundation is prevented, e.g., a ventilating fan mounted on vibration isolators. This isolation permits the installation of

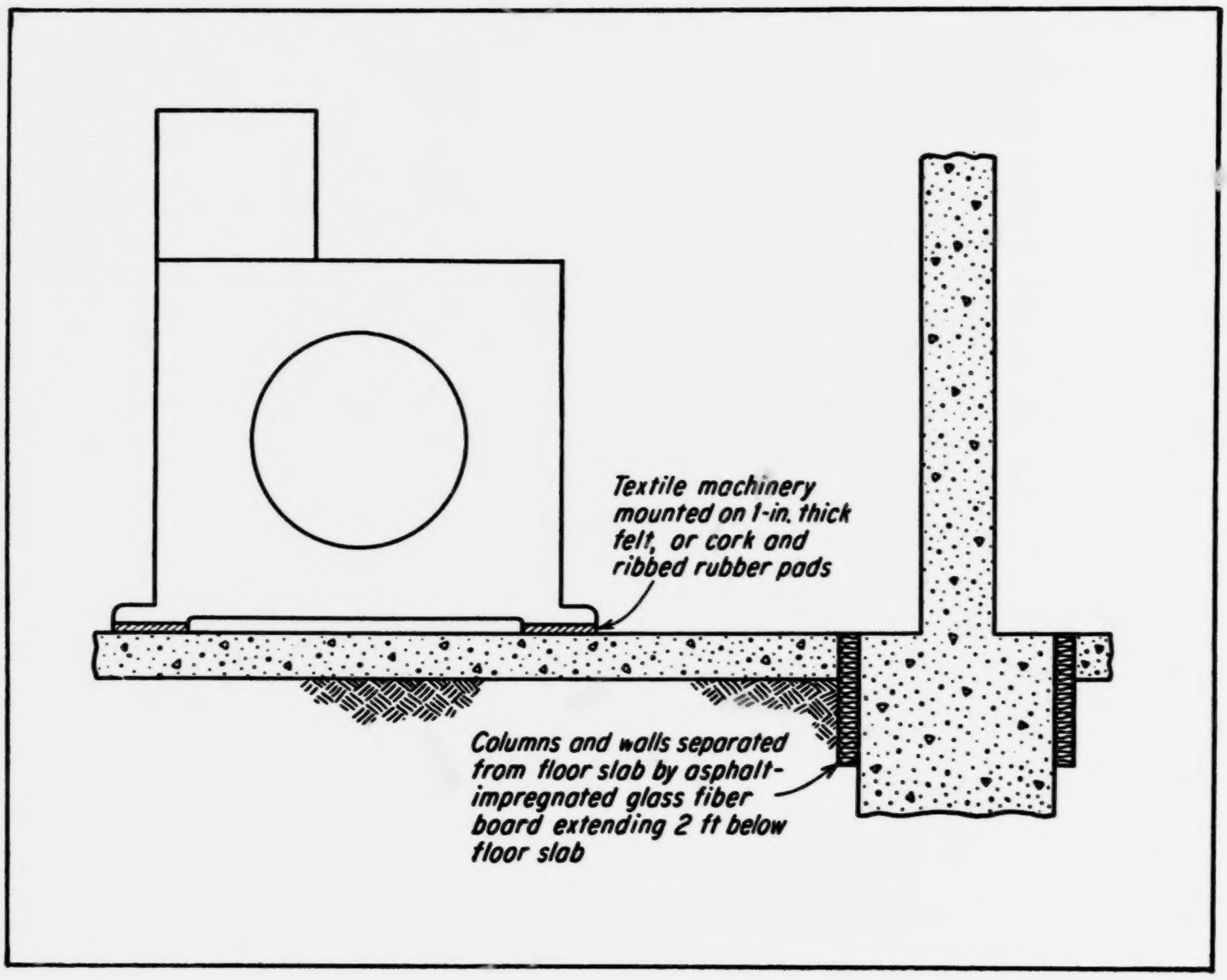
Textile machinery mounted on 1-in. thick felt, or cork and ribbed rubber pads
Columns and walls separated from floor slab by asphalt-impregnated glass fiber board extending 2 ft below floor slab

Figure P.1. Vibration break between the basement floor slab and wall of a building to reduce the transmission of noise and vibration to other parts of the structure. (Reprinted from Case Histories of Machine and Shop Quieting, contained in "Noise Reduction", by L.N. Miller, McGraw-Hill Book Co., New York, 1960).

the isolated equipment in upper story locations or on floor slabs without special foundations. In addition to its basic function, this type of isolation reduces impact and internal machinery shock, increases the life of the equipment at higher operating speeds and at reduced maintenance cost.

(b) Passive isolation, in which harmful motion from a substructure to a device mounted on it is reduced. This is used for the installation of precision instruments, allowing their placement wherever space is available or where work flow requires.

In either case, the vibration isolation is designed according to the same principles.

The source of vibration usually has a predominant frequency at which it vibrates; this is called the "disturbing frequency" or "driving frequency". The resilient mount with the weight of the equipment or machine on it will have its own "resonant frequency" or "natural frequency of oscillation" at which it will oscillate if given a deflection and then allowed to move on its own (P-2, P-8, P-9, P-13, P-14). The more deflection in the system the lower is its natural frequency (P-21). The degree of vibration isolation provided by the resilient mount will depend on the ratio of these two frequencies: the driving frequency and the natural frequency. The natural frequency of the resilient mount has to be lower (at least two times) than the driving frequency if any vibration isolation is to be obtained. No vibration isolation will be achieved if the natural frequency of the resilient mount is higher than the driving frequency. If the two frequencies are equal, or nearly equal, the resilient mount will make the situation worse, i.e., more vibration will be transmitted as if no resilient mount were used at all (P-2, P-21, P-32).

The amount of deflection of the resilient mount resulting from the dead weight of the supported load is called "static deflection", or "static displacement" (P-2, P-8, P-12, P-21). The relation between disturbing frequency, resonant frequency, static deflection and per cent reduction of vibration of a mass on a resilient support is expressed graphically in Figure P.2 (P-2).

It is quite obvious that a resilient mount must be selected with utmost care, particularly when the frequency of vibration is quite low. The mounting system should be neither overloaded nor underloaded and it should provide a resonant frequency several times lower than the lowest frequency of vibration to be isolated (P-2).

P.3 Materials for vibration control

Various resilient materials are used in vibration isolation, as follows (P-4, P-6, P-10, P-12, P-15, P-17, P-18, P-19, P-20, P-21, P-22, P-24, P-31, P-33, P-36, P-37, GB-43):

(a) Metal springs. They can provide a large range of deflections depending on the dimensions and materials used in their design. They are interchangeable, resist corrosion by oil and water, are unaffected by extremes of temperature. They have the disadvantage of transmitting high frequencies readily; this can be minimized, however, by eliminating direct contact between the spring and the supporting structure.

(b) Rubber mountings. They are used mostly to isolate small machinery and mechanical devices, such as engines, motors, instruments, etc.,where the very long life and higher efficiency provided by metal spring mountings are not essential. They tend to lose their resiliency as they age: their life is about 5 to 7 years.

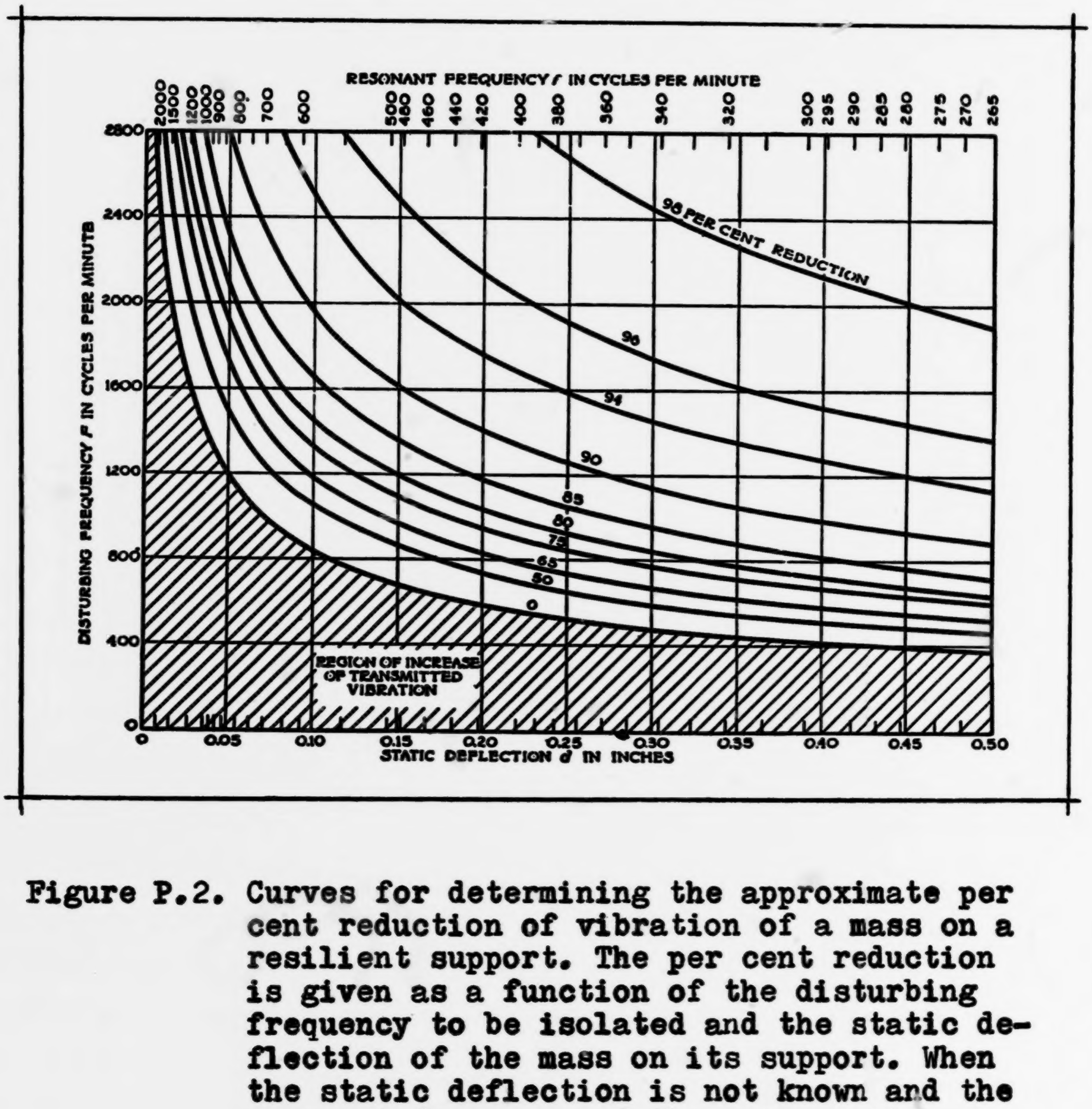

Figure P.2. Curves for determining the approximate per cent reduction of vibration of a mass on a resilient support. The per cent reduction is given as a function of the disturbing frequency to be isolated and the static deflection of the mass on its support. When the static deflection is not known and the resonant frequency of the mass on its support is known, the upper horizontal scale should be used. (Reprinted from Acoustical Designing in Architecture by V.O. Knudsen and C.M. Harris, John Wiley and Sons, New York, 1950).

(c) Resilient pads, including various materials with inherent damping; such as, glass fibre, foamed plastic, cork, felt, sponge rubber, lead-asbestos, etc.

Glass fibre is used in the form of blankets, boards, or small blocks. They combine chemical inertness, thermal efficiency, resistance to moisture, and fire safety.

Corkis the oldest material used for vibration isolation. To obtain sufficiently large deflection, the machine to be isolated is mounted usually on a large concrete block, separated from the surrounding foundation by layers of cork slabs. Cork should be subjected to a pressure of between 7 and 20 psi.

The isolation efficiency of felt will be best exploited by using the smallest possible area of the softest felt, in maximum thickness, under a static load that the felt will resist without excessive compression or loss of structural stability. Its use is recommended in $\frac{1}{2}$" to 1" thickness with an area of 5 % of the total area of the base. It is particularly useful in the isolation of vibrations in the audio-frequency range.

Besides the listed vibration isolators, other vibration-control devices are specially manufactured using or combining the isolating materials described before; hangers, clips, chairs, special rubber mounts, metal springs with auxiliary damping features, rail-type mounts, flexible hose connections, etc., are typical examples of commercial vibration isolators (M-16, P-6, P-13, P-15, P-24, P-36).

Figure P.3 illustrates the relation between the static deflection (displacement) and the natural frequency of commonly used vibration isolators (P-12).

Figure P.4 shows the practical application of certain resilient mounts in conjunction with the vibration isolation of a reciprocating compressor (N-6).

Detailed information on the properties of various resilient mounts recommended for use in vibration isolation is available in commercial and technical literature (P-3, P-9, P-12, P-13, P-15, P-19, P-21, P-24, P-26, P-36).

Additional recommendations for vibration control were given throughout subsection M.6.

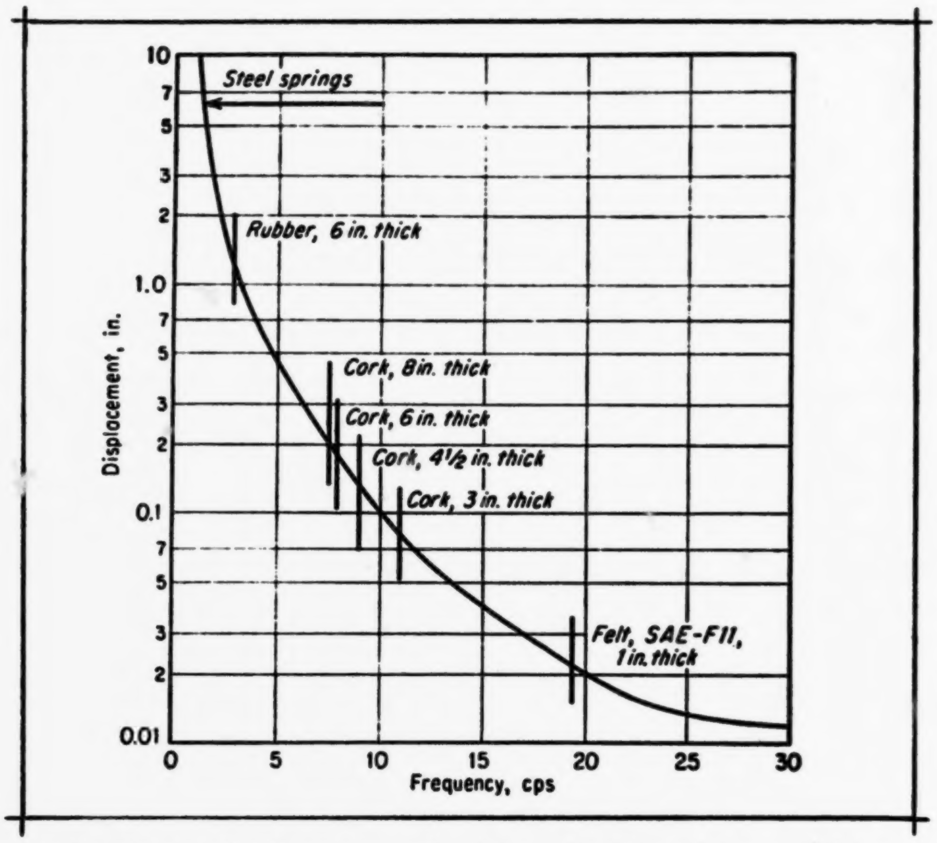

Figure P.3. Relation between static deflection (displacement) and natural frequency of commonly used vibration isolators. (Reprinted from Isolation of Vibration, contained in "Noise Reduction", by D. Muster and R. Plunkett, McGraw-Hill Book Co., New York, 1960).

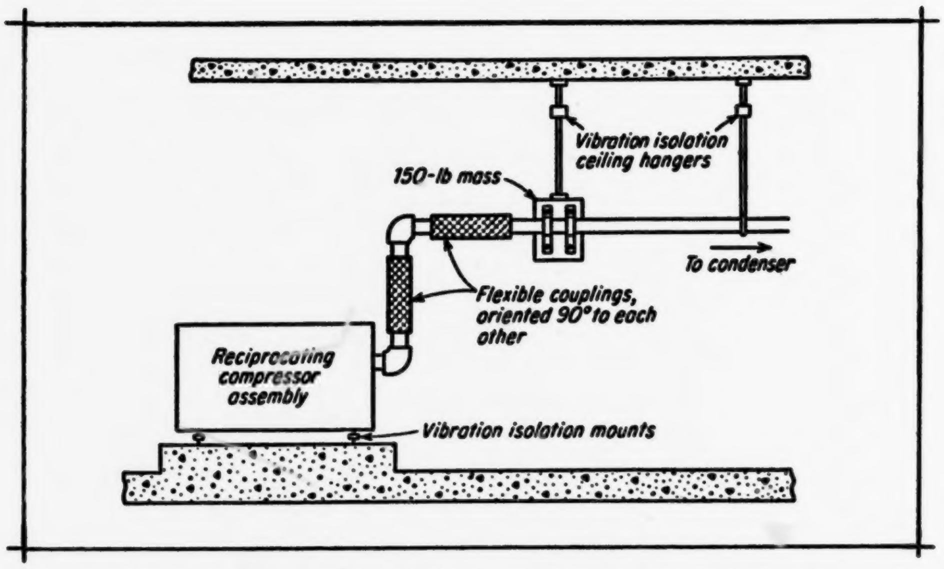
Vibration isolation ceiling hangers
150-lb mass
To condenser
Flexible couplings, oriented 90° to each other
Reciprocating compressor assembly
Vibration isolation mounts

Figure P.4. Practical application of resilient mounts in conjunction with the vibration isolation of a reciprocating compressor. (Reprinted from Case Histories of Machine and Shop Quieting, contained in "Noise Reduction", by L.N. Miller, McGraw-Hill Book Co., New York, 1960).

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relative to Section P: "Vibration Control"

(See list of abbreviations on page 1)

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Section R. Noise Criteria

- R.1 Damage to hearing
- R.2 Maximum permissible noise levels
- R.3 Criteria for Office spaces
- R.4 Noise control requirements in building codes and bylaws
  - R.4.1 The National Building Code of Canada
  - R.4.2 Foreign building codes
- References

The need for effective noise control in buildings derives from the fact that noise affects people in the following ways (M-26, R-1, R-2, R-3, R-4, R-13, R-15, R-20, R-21, R-22):

(a) it can be so loud as to cause temporary or permanent damage to the ear;
(b) it can interfere with listening to speech or music;
(c) it may cause deterioration of work performance; and
(d) it can be annoying and distracting.

As to the annoying and distracting effect of noise, people will vary considerably in their reaction, described in subsection M.1. If it is a question of damage to hearing, or interference with listening to speech or music, a person's reaction is more limited.

The basic problem in designing for noise control is to predict how the expected noise is likely to interfere with the occupancy in the room under consideration and then to set limits to the path of intruding or spreading noise in order to avoid any harmful interference. To do so, various criteria, discussed briefly in this Section, will have to be considered, depending on the type and delicacy of the noise control problem (R-22).

R.1 Damage to hearing

Noises so loud (about 150 dB) that they cause immediate damage to hearing do not occur normally in buildings; they may occur, however, near Airports. In such special cases, precautions are required to avoid the risk of people accidentally entering the damage zone without ear muffs (R-1, R-5, R-22, S-166).

Noise levels high enough to cause temporary or permanent deafness occur in industry. Various criteria have been produced giving the maximum noise levels which must not be exceeded if temporary or permanent deafness (complete or partial) is to be avoided (R-1, R-4, R-8, R-9, R-12, R-13, R-27, R-30). If existing noise levels measured in a very noisy room exceed the dangerous levels established in the corresponding criteria, some measure will have to be taken (described in subsection M.6) in order to reduce the noise and to protect the workers (R-12, S-164, GB-41).

R.2 Maximum permissible noise levels

When the probable or existing noise level of an exterior noise source has been determined (by measurement, estimation, analogy, etc.), the acceptable noise level in the receiving room has then to be established. The difference between probable or existing level at the source and acceptable noise level at the recipient's position will suggest the degree of noise reduction to be achieved (M-26). Criteria developed in the last decade enable us to specify those permissible noise levels which will provide a satisfactory environment for listening to speech and music.

The recommended maximum permissible or desirable noise levels (in the representative octave bands) in various occupancies can be specified in terms of Noise Criterion curves (or NC curves), developed by L.L. Beranek and illustrated in Figure R.1 (R-11). These NC curves are recommended for specification of the desired amount of background noise levels for various occupancies wherever a favorable relation between the low frequency and the high frequency portion of the spectrum is desired. Table R.1 shows how permissible noise levels in various occupancies (with ventilating system, if any, operating, and with normal outside traffic conditions) can be specified in terms of NC curves (M-26, R-4, R-6, R-11, R-22, S-30, S-123, GB-52). It is assumed that the infiltrating exterior noise is meaningless, because if intruding noise constitutes meaningful

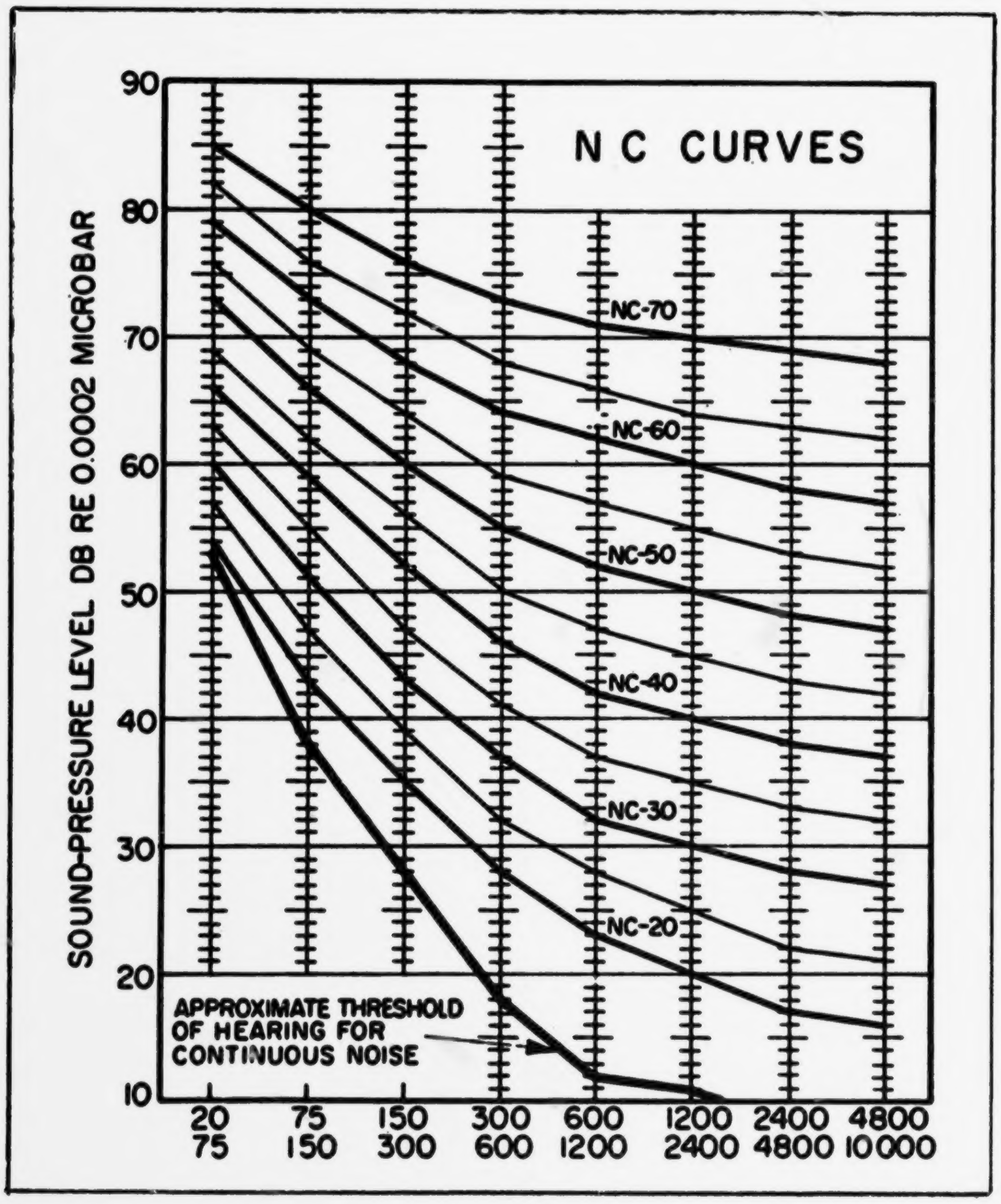

Figure R.1. Noise Criterion curves (NC curves) for use with Tables R.1 and R.3 in determining the permissible (or desirable) sound pressure levels in eight octave bands, for various occupancies. The NC number of each curve also specifies the corresponding Speech Interference Level (SIL), in decibels, used as a criterion in the noise control of Offices. Each NC curve has a loudness level in phons that is 22 units greater than the SIL in decibels. (Reprinted from Revised Criteria for Noise in Buildings by L.L. Beranek, Noise Control, Jan. 1957).

communication (e.g., speech or music), other criteria apply; their discussion falls beyond the scope of this study (R-15, R-17, R-18, R-19).

Table R.1. Recommended Noise Criteria for rooms

Type of space	recommended NC curve of Figure R.1
Concert Halls	NC 15-20
Broadcast Studios, Recording Studios	NC 15-20
Opera Houses	NC 20
Legitimate Theaters	
more than 500 seats	NC 20
up to 500 seats (no amplification)	NC 20-25
Music Rooms	NC 25
Classrooms	NC 25
Conference Rooms for 50	NC 25
Television Studios, Motion Picture Studios	NC 25
Assembly Halls	NC 25-30
Apartments and Hotels	NC 25-30
Homes (sleeping areas)	NC 25-35
Motion Picture Theaters	NC 30
Churches	NC 30
Courtrooms	NC 30
Conference Rooms for 20	NC 30
Hospitals (Patient Rooms)	NC 30
Libraries	NC 30
Restaurants	NC 40-45
Coliseums for sports only (with amplification)	NC 50

If a noise has to be reduced to inaudibility, then the permissible noise levels are specified in Figure R.1 by the curve representing the "approximate threshold of hearing for continuous noise" (R-4, R-11).

Figure R.2 represents an alternate family of Noise Criterion curves (NCA curves) recommended for use where a maximum compromise due to the economic factor is necessary (R-11).

R.3 Criteria for Office spaces

In speech communication it is mainly the frequencies between 600 and 4800 cps which affect intelligibility. Therefore, a corresponding criterion, called Speech Interference Level (SIL), has been established that is used in assessing the effects of noise on speech. If the noise level is defined in terms of Speech Interference Levels, this means the average, in decibels, of the sound pressure levels of the noise in the three octave bands 600 to 1200, 1200 to 2400 and 2400 to 4800 cps. Table R.2 gives maximum permissible Speech Interference Levels, in decibels above 0.0002 microbar, which barely permit satisfactory perception of natural adult male speech at specified distances and voice levels (R-4, R-10, R-16, R-22, R-30).

Table R.2. Maximum Speech Interference Levels (i.e., average of the three octaves between 600 and 4800 cps), in decibels above 0.0002 microbar.

Distance from speaker, ft	normal voice	raised voice	very loud voice	shouting
0.5	71	77	83	89
1	65	71	77	83
2	59	65	71	77
3	55	61	67	73
4	53	59	65	71
5	51	57	63	69
6	49	55	61	67
12	43	49	55	61

Values of Table R.2 apply when no reflecting surface is nearby, and listener and talker are facing each other (R-4).

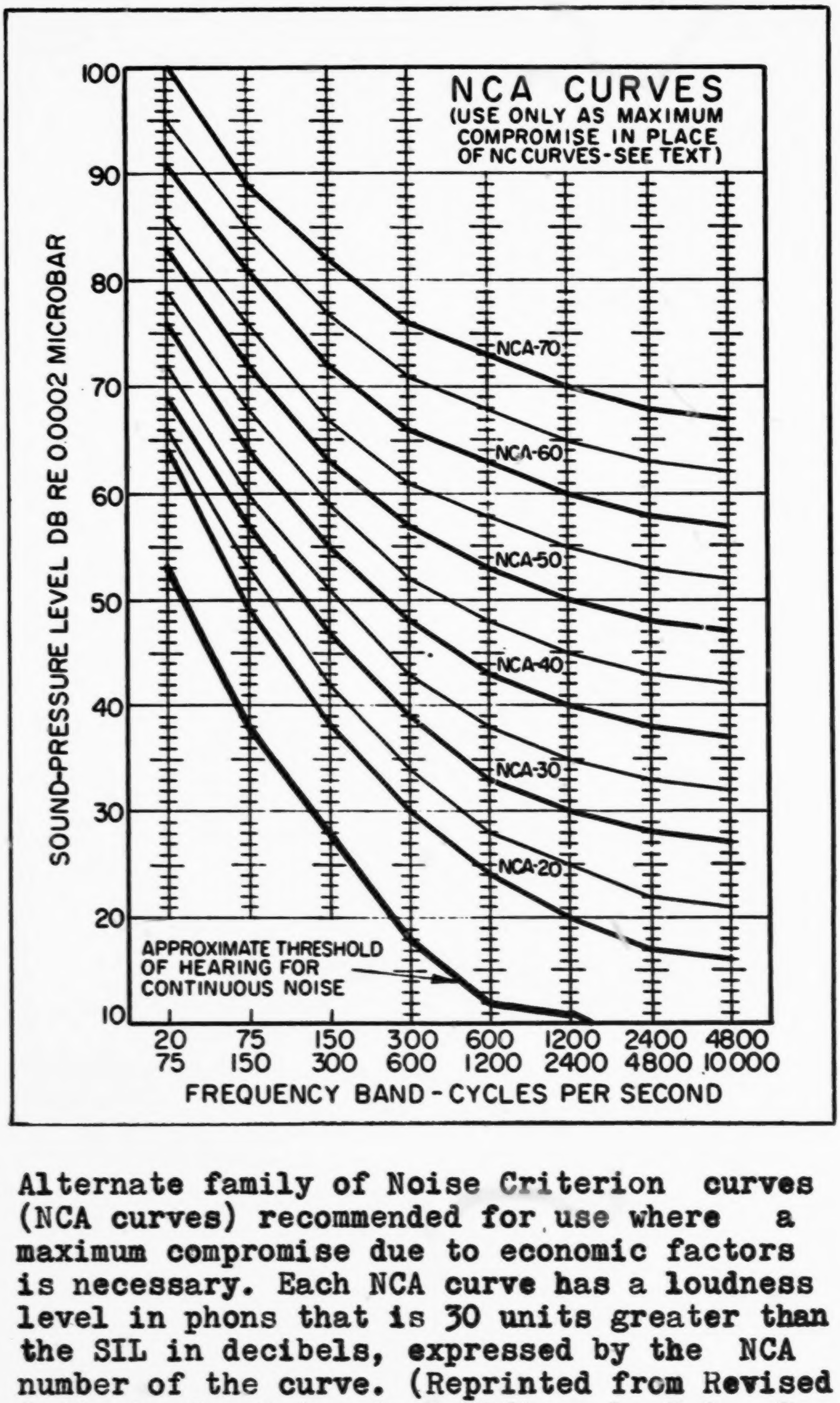

Figure R.2. Alternate family of Noise Criterion curves (NCA curves) recommended for use where a maximum compromise due to economic factors is necessary. Each NCA curve has a loudness level in phons that is 30 units greater than the SIL in decibels, expressed by the NCA number of the curve. (Reprinted from Revised Criteria for Noise in Buildings by L.L. Beranek, Noise Control, Jan. 1957).

Two criteria can be used jointly to evaluate noise conditions in Offices: the SIL in decibels,and the loudness levels in phons; their relationship is described in Figures R.1 and R.2. Figure R.3 illustrates the relation of subjective noise ratings of Executive Office personnel to SIL and loudness level; since speech is important in these Offices, an SIL of about 30 dB will be regarded as "quiet", while an SIL of about 55 dB will be considered as "noisy" in such an Office by its occupants (R-4, R-6, R-10, R-11, R-13, R-16, S-123).

Figure R.4 illustrates the relation of subjective noise ratings to SIL and loudness level for Secretarial and large Engineering Drafting Rooms where noise and speech communication are not so important. Upper parts of Figures R.3 and R.4 also show the SIL ranges for telephone use, extending from satisfactory to unsatisfactory (R-4, R-6, R-11, R-16, R-22).

These criteria apply to both intruding noises and to noises originating within the Offices themselves. It must be noted, however, that internal noises, being under the control of Office personnel, are never as critical as those coming from outside (R-4).

On the basis of extensive study of noise in Office spaces and of observations in Industrial Buildings, L.L. Beranek recommends that the NC curve for a particular Office space be selected with the aid of Table R.3. If in certain cases extreme economy is imperative, the corresponding NCA curve should be substituted for the proposed NC curve (R-6, R-11).

In selecting an NC curve or an SIL for a particular specification, the architect or the acoustical consultant will have to make a judicious judgement, partly because of frequent deviation (often disagreement) in people's reaction towards noise and in local customs, and partly because of the frequent lack of funds for noise control work (R-6, S-123).

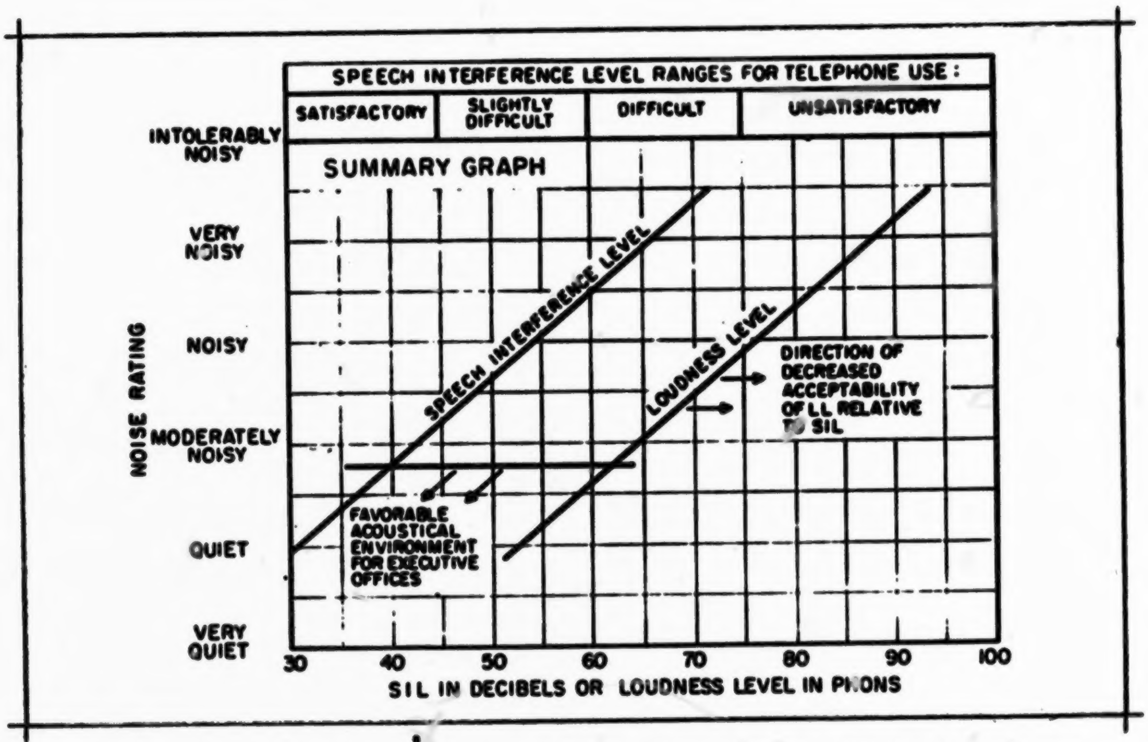

Figure R.3. Rating of Executive Offices. (Reprinted from Revised Criteria for Noise in Buildings by L.L. Beranek, Noise Control, Jan. 1957).

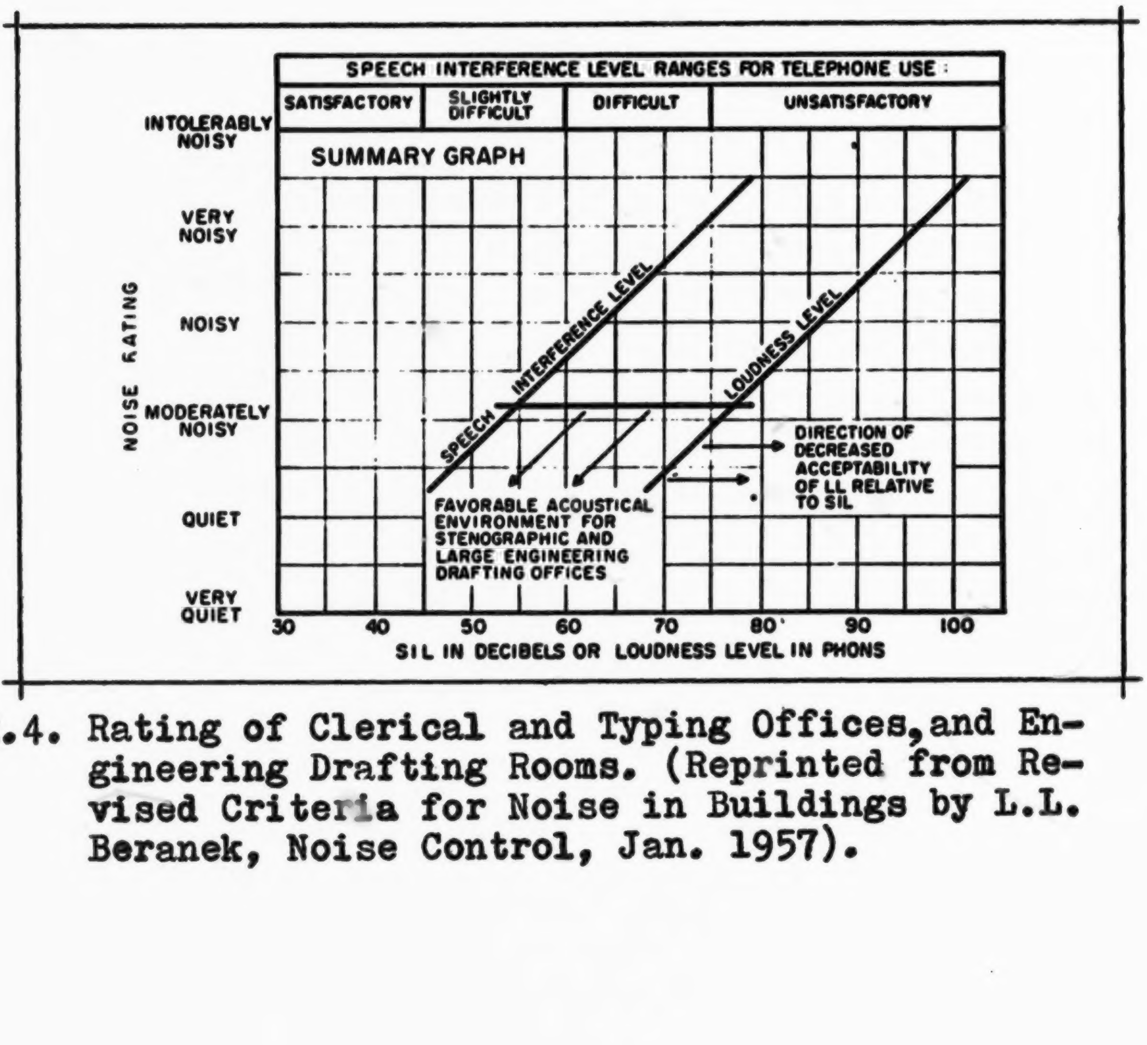

Figure R.4. Rating of Clerical and Typing Offices, and Engineering Drafting Rooms. (Reprinted from Revised Criteria for Noise in Buildings by L.L. Beranek, Noise Control, Jan. 1957).

Table R.3. Recommended Noise Criteria for Offices. (Reprinted from Criteria for Noise and Vibration in Buildings and Vehicles, contained in "Noise Reduction" by L.L. Beranek, McGraw-Hill Book Co., New York, 1960).

NC curve of Figure R.1	communication environment	typical application
20-30	Very quiet Office; telephone use satisfactory; suitable for large conferences	Executive Offices and Conference Rooms for 50 people
30-35	"Quiet" Office; satisfactory for conferences at a 15 ft table; normal voice 10 to 30 ft; telephone use satisfactory	Private or semiprivate Offices, Reception Rooms and small Conference Rooms for 20 people
35-40	Satisfactory for conferences at a 6 to 8 ft table; telephone use satisfactory; normal voice 6 to 12 ft	Medium-sized Offices and industrial business Offices
40-50	Satisfactory for conferences at a 4 to 5 ft table; telephone use occasionally slightly difficult; normal voice 3 to 6 ft; raised voice 6 to 12 ft	Large Engineering and Drafting Rooms, etc.
50-55	Unsatisfactory for conferences of more than two or three people; telephone use slightly difficult; normal voice 1 to 2 ft; raised voice 3 to 6 ft	Secretarial areas (typing), accounting areas (business machines), Blueprint Rooms, etc.
Above 50	"Very noisy"; Office environment unsatisfactory; telephone use difficult	Not recommended for any type of Office

The noise control problem can be quite serious if the intrusion of intelligible speech has to be excluded. When the occupant of a room is well protected against intelligible communication originating from an adjacent space, in other words, he has an assurance of not being overheard, he is said to have speech privacy. The provision for speech privacy is associated with a rather complex acoustical design procedure; noteworthy efforts have been made to simplify this procedure (R-17, R-18, R-19).

R.4 Noise control requirements in building codes and bylaws

Requirements (standards) or recommendations for the sound insulation between various occupancies, contained in building codes, standards, bylaws, etc., constitute important criteria for the control of noise (R-23, R-25, R-26, R-27, R-28, R-29, R-30, R-31, R-32, R-33, R-34, R-35).

Noise control requirements should be considered as a fundamental component in the environmental control of buildings. The otherwise reasonable and justified trend of continuous search for lighter, thinner, and more inexpensive building construction could not proceed in an acceptable direction (and also noise levels would further increase in buildings), (a) without building codes, standards, bylaws, etc., containing the necessary criteria for noise control, and (b) without the architect's familiarity with architectural acoustics.

The progressive national building codes throughout the world contain noise control requirements. These requirements (a) usually list sound insulation values for walls and floors in various (particularly residential) buildings, giving values for both airborne and impact sounds, and (b) sometimes also specify acceptable locations of buildings in relationship to noise sources (highways, airports, etc.).

Sound insulation requirements adopted in the bylaws of municipalities have no value unless enforced; this can be carried out, as with other technical requirements, by withholding the building permit if inspection of the building plans or of the construction should reveal disregard of the relevant acoustical requirements (R-3).

R.4.1 The National Building Code of Canada

Subsection 3.6.9 of Part 3 of the Code, entitled "Acoustical Insulation", lists TL requirements for a variety of buildings and rooms (R-3, R-34). These requirements are presented in an original form, by postulating the maximum air-borne noise levels likely to be produced by the occupancy, and then assigning maximum tolerable air-borne levels of extraneous noise. The required TL for walls and floors separating major occupancies will be the difference between the maximum level produced by one occupancy and the maximum acceptable level of extraneous noise for the adjacent occupancy. The Code recommends that this calculation should be made both ways, the greater difference being used for determining the required TL. Table R.4, part of the corresponding Table in the Code, lists the necessary values to calculate the TL of walls and floors (R-34).

Table R.4. Maximum air-borne noise levels likely to be produced by various occupancies and the maximum tolerable air-borne level of extraneous noise. (Reprinted from the National Building Code of Canada 1960, issued by the Associate Committee on the National Building Code, National Research Council, Ottawa, 1960).

Types of use of floor area or room	maximum air-borne noise produced by occupancy	maximum air-borne level of extraneous noise
	units: decibels vs. standard reference level	
Assembly Rooms with fixed seats such as Theaters, Auditoria or Concert Halls	85	30
Other Assembly Rooms where non-fixed seats may be used including Classrooms designed or intended for assembly purposes	85	30

(Table R.4 cont'd.)

Types of use of floor area or room	maximum air-borne noise produced by occupancy	maximum air-borne level of extraneous noise
	units: decibels vs. standard reference level	
Concourses, Waiting Rooms in Assembly Buildings, Rotundas, Entrance Halls	85	30
Stadia and Grandstands	85	-
Bowling Alleys, Pool and Billiard Rooms and similar areas	85	-
Classrooms	80	40
Vocational Shops	80	40
Operating and Clinical Rooms in Hospitals	80	40
Detention Quarters	80	50
Reading or Writing Rooms or Lounges in other than dwelling units	75	30
Dining Rooms in other than dwelling units	80	60
Kitchens in other than dwelling units	90	60
Rooms used for sleeping		
single rooms in other than dwelling units	80	30
Dormitory	80	40
Dwelling units, all rooms	80	30
Retail sales floors	80	60
Manufacturing or Process Rooms	90	-
Offices	80	50
Toilet and Locker Rooms	80	-
Cleaning and repair of goods	90	-
Exits; and Corridors serving as access to exits from rooms or suites	80	-
Storage	90	-

The "Housing Standards", a supplement to the National Building Code of Canada,published to regulate the construction of Residential Buildings under the National Housing Act, recommends that a minimum average TL of 45 dB should be provided between dwelling units in the same building, and between dwelling unit and any space common to two dwelling units (R-35). Tables IV, V, and VI of the same publication list various wall and floor constructions giving 45 dB average TL.

It must be mentioned that the sound insulation requirements of the National Building Code of Canada are not compulsory. They are recommendations based upon extensive research work, experience and comments by experts. It is left to the responsible authorities of municipalities to make this building code or parts of it compulsory, if they so wish. The National Building Code of Canada is, in fact, drafted in the form of a bylaw, so that it may be adopted or enacted for legal use by any municipality (R-34).

R.4.2 Foreign building codes

In the United Kingdom the Building Research Station of England has recommended the following (R-4, R-30, R-31, S-35):

(a) for walls between houses an air-borne sound insulation should be achieved as shown in Figure R.5.A. Any deviation in the unfavorable direction should not exceed 1 dB when averaged over the whole frequency range;

(b) for party walls and party floors between Apartments a higher (grade I) or a lower (grade II) degree of air-borne sound insulation should be accomplished, according to local needs and conditions; these two grades are shown in Figure R.5.B. Any deviation in the unfavorable direction should not exceed 1 dB when averaged over the whole frequency range;

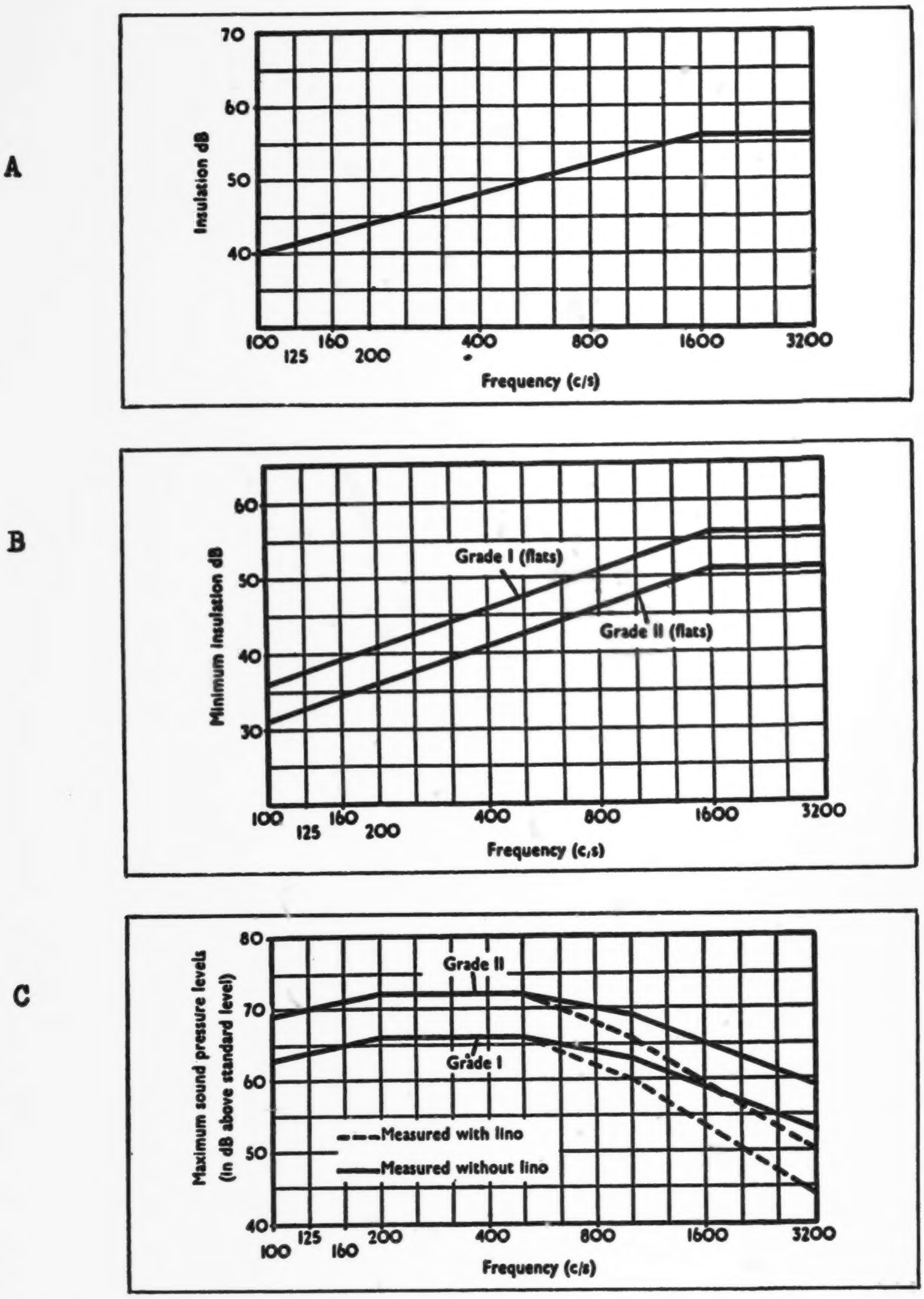

Figure R.5. Recommended criteria for the sound insulation of Residential Buildings in the United Kingdom. A: air-borne sound insulation between houses. B: air-borne sound insulation between Apartments. C: impact sound insulation between Apartments. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

(c) for impact sound insulation of floors between Apartments the sound pressure levels in the receiving room, when a standard tapping machine is operated in the source room above, should not exceed the values represented by the diagrams of Figure R.5.C. Two grades are shown in the Figure; grade I represents the highest insulation economically practicable for floors in Apartment Buildings against impact sound; grade II provides a reduced degree of insulation.

To satisfy a particular grade, a floor construction between dwelling units must meet the requirements of both air-borne and impact sound insulation.

Table R.5 compares average TL values for walls and floors between specified occupancies as recommended in the building codes of various countries (R-3, R-4, R-23, R-28, R-29, R-30, R-31, R-32, GB-29, GB-52), before about 1950.

Table R.5. Average TL values for walls and floors between specified occupancies as recommended in the building codes of various countries, before 1950.

	Average TL, decibels
Germany	
Apartments	51
Sweden	
Apartments	48
Classrooms	42
Hospital Rooms	50
Offices	40
Norway	
Apartments	50
Hospital Rooms	50
Hotel Rooms	50
Classrooms	44
Offices	40

(Table R.5 cont'd.)

	Average TL, decibels
Austria	
within the same Apartment	40
between Apartments	48
between houses	53
Holland	
Apartments	48-52
Switzerland	
Apartments	52-57
Classrooms	47-52
Offices	47-57
Hotel Rooms	52-62
Hospital Rooms	52-62

In most countries single figure requirements or recommendations for the insulation of both air-borne and impact sounds in Residential Buildings have been replaced by grading curves similar to those introduced in England (R-20).

References
relative to Section R: "Noise Criteria"
(See list of abbreviations on page 1)

Chapters of books

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Standards, codes

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Section S. Practical Noise Control

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S.1 Auditoria

The effect of site planning and architectural design on the noise control of Auditoria has been discussed in paragraph M.6.3, the most important requirement being the reduction of the Auditorium noise level, produced by all exterior and interior noise sources, to the lowest possible value (S-1, GB-21, GB-43).

The recommended Noise Criteria for various Auditoria have been listed in Table R.1. The achievement of these NC values will necessitate the consideration of Section N, "Sound Insulating Building Constructions".

Table M.3 has listed recommended horizontal distances between a road carrying heavy traffic and various Auditoria facing this road (GB-43).

Any Auditorium to be constructed on an overly noisy downtown site should be designed, if possible, with a protective (buffer) zone of rooms between exterior noise sources and the Auditorium proper; this will enable the use of less insulative enclosures around the Auditorium. Rooms located in the buffer zone (Vestibule, circulation spaces, Bars, Restaurants, Offices, etc.) should have sound absorbent ceilings.

The increase in air traffic often necessitates the design of particular sound insulating windows and roofs with properly suspended ceilings (paragraph N.3.2). The installation of a suspended ceiling is indispensable in a contemporary Auditorium in order to accommodate ventilating, air-conditioning, and electrical services above the room. The elimination of windows is an effective contribution towards the noise control of Auditoria; with ventilating and air-conditioning systems available this should be regarded as a normal design procedure where excessive outdoor noises have to be excluded (GB-21, GB-43).

If an Auditorium is subject to vibrations originating from surface or underground trains, near-by bus lines, etc., particular precautions will have to be taken to eliminate these vibrations from the building structure (H-39, H-108, N-43, N-53, GB-21, GB-43); this is discussed in Section P.

S.2 Studios

The difference between the noise control of Studios and other Auditoria is one of degree only: all noises from outside and inside the building likely to interfere with the Studio activities must be reduced to a particularly low value. It is not a question of what noise levels are comfortable or economical, but what levels must be secured if satisfactory broadcasting, telecasting, or recording is to result, described in Section J, "Acoustical Design of Studios" (J-1, J-4, J-23, J-29, J-49, J-76, S-3, S-5, S-6, S-7, S-8).

The recommended Noise Criteria for various Studios are listed in Table R.1; the provision for these NC values will require consideration of Section N, "Sound Insulating Building Constructions" (S-9). In addition, attention should be given to various general design recommendations outlined in subsection M.6.

In the architectural design of Studio Buildings the creation of buffer zones around the Studio proper is especially advantageous. The juxtaposition of various occupancies in Studio Buildings will also require utmost care to avoid unwanted noise transmission through floors (J-1, S-5, GB-43).

Table S.1 lists the tolerances of various Studios to noise in general, and also to interference from noise sources having a meaningful, intelligible content (GB-43).

Table S.1. Tolerance of Studios to noise in general and to interference from noise sources having a meaningful content. (Reprinted from Acoustics, Noise and Buildings by P.H. Parkin and H.R. Humphreys, Frederick A. Praeger, New York, 1958).

Room	rating as noise source	tolerance of incoming noise	interference
Music Studio, Radio or Recording	high	very low	very low
Talks and Drama Studios, Radio or Recording	medium	very low	very low
Control and Listening Rooms, Radio, Recording or Television	high	low	very low
Television Studios, including Dubbing Suites	high	low	very low
Recording Rooms	medium	low	low

The suppression of noise originating from ventilating and air-conditioning systems, a particularly important aspect in the noise control of Studios, has been dealt with in Section O (O-6, O-14, O-18, O-45, O-86).

S.3 Residential buildings

The most common noise sources which occur in Residential Buildings have been described in subsection M.3 (S-15, S-30, S-32, S-38, S-40, S-43).

The effects of town planning, site planning, and architectural design on the noise control of Residential Buildings have been discussed in paragraphs M.6.2, M.6.3, and M.6.4.

Recommended Noise Criteria for Homes and Apartments are listed in Table R.1 (R-15, R-17, R-18, R-19, S-15). The noise control requirements for the sound insulation between various occupancies in Residential Buildings, recommended by the National Building Code of Canada and other building codes, have been described in subsection R.4.

Tables N.2 and N.3 list average air-borne sound transmission losses for typical wall and floor constructions suitable for use in Residential Buildings. Figure N.5 illustrates a curve of maximum acceptable impact sound pressure levels for floor constructions in Apartment Houses, recommended by the Federal Housing Administration (Washington, D.C.). Additional information on the TL of various enclosures that can be used in Residential Buildings is available from many sources (N-4, N-95, S-14, S-21, S-23, S-35, GB-21, GB-29).

Residential Buildings constructed in quiet rural or suburban districts will require a higher degree of sound insulation than those built in noisy areas, because noises from the neighbors will be more readily noticed in a quiet than in a noisy surrounding. It is often noticeable that occupants of Apartments who are almost conditioned to the noisy environment of densely populated areas are less concerned about the sound insulation than those accustomed to a quiet environment (N-4).

Additional information on the soundproof furnishing of Homes and Apartments is available from various articles (S-12, S-16, S-20, S-26, S-27, S-28, S-29, S-30).

S.4 Hotels, Motels

In the noise control of Hotels and Motels three types of rooms require attention: (a) public and social rooms; such as, Dining Room, Reading Room, Ball Room, Recreation Room, Convention Rooms, etc., (b) Guest Rooms, and (c) circulation areas, such as Lobby, Corridors, etc. (S-47, S-48, S-51, GB-52).

The principal acoustical requirements in the public and social rooms are: (a) adequate protection against noises originating from exterior sources or from adjacent rooms, and (b) control of noise and reverberation within the rooms themselves. Relevant subjects have been discussed in Sections M, N, and O, and subsection F.5 (S-48, S-50). If public rooms have to be subdivided into two or more spaces by means of folding partitions, then these folding partitions should possess an average TL of 35 to 50 dB, depending on the desired function of the individual spaces.

In the main, noise control problems of Guest Rooms are identical with those encountered in Apartment Buildings, since every room of a Hotel or Motel should be considered as an isolated Apartment (S-47, S-49). An average TL of 40 to 45 dB is recommended between adjacent rooms, and between rooms and corridors for low-cost Hotels or Motels and 45 to 53 dB for high-cost ones (S-51, GB-52). Direct connection between adjacent Guest Rooms by doors should be avoided, unless acoustically efficient doors are installed.

Carpeting in all spaces is essential to eliminate impact noises.

Exterior walls should provide an average TL of 40 to 50 dB, according to local needs; openable windows limit these values.

Particular attention should be paid to the elimination of mechanical noises (Section O).

S.5 Schools

Because of the importance of favorable hearing conditions in all educational establishments, acoustics is a fundamental physical attribute that will contribute to the function of a School.

The sound control of a School requires consideration of the following:

(a) selection of the site (S-54, S-57, S-60);
(b) site planning, described in paragraph M.6.3 (S-53, S-57, S-75);
(c) room-acoustical design of Classrooms, Lecture Halls, Auditorium, Theater, Gymnasium, Music Rooms, Audio-Visual Rooms, etc.; this has been discussed in Sections F, G, and H (S-53, S-59, S-71);
(d) control of exterior and interior noise throughout the entire building (S-55, S-56, S-62, S-63, S-69, S-76).

General design considerations, also applicable to Schools, have been reviewed in paragraph M.6.4. Recommended Noise Criteria for various School Rooms are listed in Table R.1 (subsection R.2).

For purposes of sound insulation, the British Standard Code of Practice groups various rooms of Schools as following (R-30):

Class A: noise producing, such as Workshops, Kitchens, Dining Rooms, Gymnasia, indoor Swimming Pools, and Boiler Rooms;
Class B: noise producing, but needing quiet at times, such as Assembly Halls, Lecture Halls, Music Rooms, Commerce and Typing;
Class C: average, such as General Classrooms, Practical Rooms, Laboratories, and Offices;
Class D: rooms needing quiet, such as Libraries, Study Rooms; and
Class E: rooms needing privacy, such as Medical Rooms, and Staff Rooms.

The minimum noise reductions recommended by the British Standard between these rooms are the following:

between rooms of Class A	25 dB
between rooms of Class C or D	35 dB
between rooms of Class B or E	45 dB

When a room is likely to have a dual use, the higher noise reduction value should be used. The recommended minimum noise reduction between rooms of different classes is 45 dB, subject to various conditions.

Acoustical problems are increasing in the contemporary School due to several changes: (a) changes from the old ways of doing things academically, and (b) the concept of changeability is being incorporated in to-day's building, recognizing change as an important element in educational progress (S-73).

Currently there is a remarkable movement in Classroom layout that advocates absolute freedom of activity through the elimination of doors and permanent partitions (S-62, S-65, S-72, S-74, S-76); this trend favors the use of movable partitions, thereby providing a possibility of adjusting the size of the Classroom to suit momentary space requirements. In some cases partitions are completely eliminated from a larger space where several teaching groups meet simultaneously (S-52, S-66, S-67, S-68, S-73, S-76). This flexible arrangement admittedly eliminates the cost of partitions, even though more floor area has to be provided per student than would be necessary in a conventional layout. The revolutionary layout of open Classrooms challenges the long-established belief that 35 to 45 dB average TL is mandatory between Classrooms (S-74). It appears that the standard stereotype Classroom layout is losing in popularity and several new arrangements are emerging (S-72). One is inclined to conclude that the overall environment of specific Classrooms seems to be more important than the degree of acoustical separation between Classrooms (S-74).

Subdivisible School Auditoria are often built, thus accommodating 4 to 5 additional Classrooms within the Auditorium space, and separated by operating (moving) partitions. The combination of a relatively high ambient noise level with high-performance operating partitions make possible the simultaneous use of all spaces created by subdivision (S-70, S-73, S-76).

S.6 Hospitals

The Hospital is unquestionably a building whose occupants are particularly affected by noise. The selection of a suitable site, therefore, must be considered with special attention to possible traffic noises of highways, railroads, airport and also to noise originating from parking areas (paragraph M.6.3).

Exterior noises are exceeded in number by the interior noises mainly because inherent mechanical units of a Hospital are fundamentally noisy. Interior noises are caused by (S-85):

(a) mechanical equipment (machinery, boilers, pumps, fans, ventilators, transformers, elevators, air-conditioning equipment, etc.);
(b) operational facilities (plumbing units, refrigerators, ice machines, dishwashers, sterilizers, autoclaves, housekeeping facilities, etc.);
(c) patient service facilities (oxygen tanks, carrier carts, instrument cases, etc.);
(d) personnel activities (staff talk and walking in corridors); and
(e) patients and visitors.

In the acoustical design of Hospitals it is essential to specify the Noise Criteria (shown in Figure R.1) of both important rooms and various pieces of equipment. Table S.2 lists Noise Criteria for various rooms of Hospitals, recommended by L.S. Goodfriend and R.L. Cardinell (S-85).

Table S.2. Recommended Noise Criteria for various rooms in Hospitals.

Room	recommended NC curve of Figure R.1
Patient Room	NC-30
Nurses' Station	NC-35
Surgery and Delivery	NC-40
Private Office	NC-35
General Office	NC-45

The average TL against air-borne noise between Patient Rooms should be about 45 to 50 dB depending on the importance given to acoustical considerations (R-30, S-84). Special sound insulation should be provided for Maternity and Nursery Rooms and for spaces of acute sufferers who are likely to be noisy (S-79); between such rooms with occupants particularly susceptible to noises, an average TL of about 50 to 55 (sometimes 60) dB is required (GB-52). For walls between Patient Rooms and Corridor an average TL of about 45 dB seems to be satisfactory; efficient sound insulating doors should be used in these walls. The use of a floating floor is seldom required in Hospitals (GB-52).

To achieve the design goals for noise control the aspects outlined in subsection M.6, and in Sections O and P should be observed. In addition, attention should be given to the following recommendations (S-78, S-79, S-80, S-81, S-82, S-84, GB-43, GB-52):

(a) in selecting a site and in site planning consideration should be given to the following items: distance from exterior noise sources; effect of nearby high buildings as noise reflectors; nearby traffic conditions (highway grades, traffic volume, traffic lights, etc.); use of certain buildings as sound barriers;

(b) loading platforms and parking areas (for visitors, staff members, and personnel) should be carefully located, particularly to avoid noise at undesirable times;

(c) mechanical plant should be placed preferably in a separate building;

(d) closed courts should be avoided, unless rooms facing the court are air-conditioned with hermetically sealed fixed windows;

(e) corridors, as potential noise sources, should be avoided or planned as short as possible;

(f) doors to opposite rooms should be staggered; all doors should be fitted with silent closers;

(g) equipment, operational facilities and patient service facilities should be selected, installed and operated for minimum noise output; every item of equipment should be considered to see if hard materials could not be replaced by some resilient materials.

Rooms to be used for instruction purposes, conferences, or meetings, should be treated so that they provide good acoustical conditions for the intelligibility of speech.

Virtually all rooms of a Hospital should be treated to a greater or lesser extent with sound absorptive material to reduce the noise level; this acoustical treatment used for noise reduction purposes is a supplement to, not a substitute for, satisfactory insulation between adjacent rooms (S-79).

Acoustical materials (discussed in Section E) should be carefully selected so that they do not interfere with sanitary requirements of the Hospital. Plastic faced mineral fiber tiles, metal pan acoustical ceiling with mineral wool pad, or mineral wool blankets covered with perforated boards will meet these requirements. Floors should be covered with a resilient covering (rubber tile, cork tile, vinyl tile, linoleum, etc.) to reduce impact noises.

S.7 Audiometric Rooms, Sound Laboratories

Used for audiometry and for acoustical measurements and research, these rooms are practical applications of discontinuous construction, discussed briefly in paragraph N.3.5. Since their design and construction constitutes specific problems of architectural acoustics, their discussion falls beyond the bounds of this study. Information on these types of rooms is available from a number of articles (S-87, S-89, S-90, S-91, S-92, S-97, S-100, S-102, S-104, S-105, S-107, S-108, S-109).

S.8 Museums, Libraries

In Museums and Libraries every reasonable effort should be made to provide a quiet environment essential for study or reading in the Library or for the contemplation of the works of art on display in Museums (S-112). This will suggest the use of a reasonable amount of sound absorbing materials along the boundary surfaces in order (a) to reduce R.T. to a minimum, and (b) to reduce any noise within the room created by the dropping of a book, closing of a door, coughing, talking, or other activities (S-111, S-113, S-115).

Recommended Noise Criterion for Libraries has been listed in Table R.1 (subsection R.2).

S.9 Offices

Practical noise control of Offices involves (a) protection against exterior noise from various sources, and (b) adequate insulation (horizontally and vertically) between individual spaces in order to secure speech privacy, i.e., speech originating in one Office should not be intelligible in an adjacent Office (M-122, S-116, S-117, S-118, S-119, S-120, S-12!).

The following are the most common noise sources of Offices (S-119, S-120, GB-43):

(a) outdoor noises originating from traffic, or from playgrounds, arenas, etc.;

(b) industrial noises associated with manufacturing processes, factory machinery, construction projects, marshalling yards, etc.;

(c) mechanical noises caused by heating, ventilating, and air-conditioning systems, plumbing, elevators, escalators, pneumatic tubes, etc.; and

(d) typical Office noises created by business machines, teleprinters, typewriters, call systems, telephones, speech, circulation on hard floor finishes, doors, etc.

The required Noise Criteria for Offices have been listed and discussed in subsections R.2, R.3, and R.4; to achieve them, the "Methods of noise control" outlined in subsection M.6 should be observed in conjunction with Sections O, "control of Mechanical Noises", and Section P, "Vibration Control". Transmission loss values for walls and floors between Offices, recommended in various building codes, are listed in Table R.!(S-123).

The British Standard recommends the following minimum average transmission losses in Offices (R-30):

(a)	for walls between Offices requiring quiet, on a quiet site where privacy is required	45 dB
(b)	for walls between Offices requiring quiet, but on a noisy site where a lower degree of privacy is tolerable	40 dB
(c)	for walls between Clerical Offices where noise is not a major nuisance	20-30 dB
(d)	for floors (to be furnished with a resilient finish)	40 dB

The division of rentable Office space by light-weight, movable partitions, subsequent to the completion of the building, is becoming increasingly usual. The acoustical performance of most of these partitions, erected up to the underside of a suspended ceiling, seldom exceeds a TL of 25 to 30 dB; this is insufficient in most cases, unless the background or traffic noise is so high that it masks (drowns out) the sounds coming through the light-weight partition.

With light-weight, prefabricated, movable partitions, built up to the suspended ceiling, particular attention should be paid to make sure that (S-118, S-121, S-122, S-123):

(a) all apertures, gaps, and joints at side walls, floor, and ceiling are properly sealed, and

(b) sound barriers are provided above the ceiling with a noise reduction characteristic that will not be reduced by ducts, conduits and cables installed in the ceiling space.

Additional information on suspended ceilings was given in paragraph N.3.2 (S-123).

The noise reducing effect of acoustical treatment in rooms has been discussed in paragraph M.6.8.

Various nomograms are published in articles as a guide for the quick determination of the required insulation of Office partitions, depending on the sound level of the noise source, on the prevailing background noise conditions, and on the permissible noise level in the Office under consideration (S-119, GB-43).

S.10 Restaurants, Cafeterias

The acoustical problem in Restaurants and Cafeterias is simply one of reducing reverberation and noise, mostly created within the room or in adjacent spaces, such as Kitchen, Service Rooms, etc. (S-124, S-126).

In middle and high class Restaurants, elements of the room decoration (draperies, carpets, wall panelings, lighting fixtures, flowers, etc.) will contribute beneficially to sound absorption. In addition, the use of acoustical treatment along available (mostly ceiling) surfaces should be considered. To achieve the required degree of noise reduction in Cafeterias, it is important to treat acoustically the ceiling of the dining, serving and all other adjacent areas as well.

The use of a Sound Lock between dining space and Kitchen is always advantageous to exclude Kitchen noise from the dining area.

Those acoustical materials should be used in Restaurants and Cafeterias which can withstand humidity, can be cleaned easily, and painted repeatedly (S-124, S-126).

Table R.1 shows the recommended Noise Criteria for Restaurants.

S.11 Transportation Buildings

Even though every Transportation Building (Railway Station, Subway Station, Bus Terminal, Harbor, etc.) has its own specific problem of eliminating the noise logically associated with its function, this subsection will outline primarily noise control problems of Airports (S-129, S-130, S-133, S-137).

Airports have always presented a most annoying sonic environment, seriously affecting passengers, employees, and neighbors alike. In spite of the fantastic amount that is being spent on noise suppression devices, it is anticipated that Airport noise, resulting mainly from take-off operations, is likely to increase in the future (S-127, S-128).

The major function of a large city Airport is to provide adequate facilities for the transport of poeple and freight; however, it also provides a large number of additional services to both the airlines and their customers (Executive, Clerical and Engineering Operation Offices; Ticket Counters, Shops, Lunch Counters and luxury Restaurants; maintenance, baggage, and cargo handling areas, etc.). Since functional activities within most of these occupancies include either direct speech or telephone conversation, the acoustical criteria for the noise control of Airports should be established with the intent of securing adequate speech privacy for the various spaces. For this reason, and also because the noise of turboprops and turbojets is disturbing predominantly in the high frequency range, it follows that the controlling frequency range in the acoustical calculations should be between 600 and 4800 cps, with the logical use of the Speech Interference Levels (R-4, R-11, S-130).

The TL of building materials, which might be considered for wall and roof constructions of Airports, should be, therefore, particularly favorable in the SIL bands (S-130).

Detailed information on various aspects of the noise control of Airports is available from a number of sources (S-129, S-130, S-131, S-133, S-136, S-137, S-138).

S.12 Industrial Buildings

Noise levels of various industrial noise sources, as listed in Table M.1, clearly indicate the necessity for an effective noise control in several industries.

In the noise control of Industrial Buildings the requirements are the following (M-122, S-150, S-167, GB-21, GB-52):

(a) to provide a reasonable acoustical environment for the individual workmen (machine operators) who produce the noise;

(b) to facilitate speech communication among operators, to the required degree;

(c) to protect other workers or employees, either close to the noise source or at some other location within the same building; and

(d) to prevent the transmission of noise into adjacent buildings or into the surrounding community.

Workmen can be protected either by introducing sound absorbent materials into the noisy space, outlined in paragraph M.6.8, or by suppressing the noise at the source by the use of a sound-reducing enclosure (screening) around the machine making the noise; this was described in paragraph M.6.1 (S-141, S-149, S-153, S-155, S-163). If, after all these measures, the noise level is still above the tolerable degree, the workers should protect their hearing by means of suitable ear defenders (S-160, S-164, S-166, S-167). In conjunction with the use of noise reducing enclosures around noisy machines, it must be noted that the operator of the offending equipment is seldom critical about the noise produced by the machine under his control; he will often check the efficiency and performance of the machine by the noise it generates.

Considerable noise reduction may be achieved in a noisy industrial building by means of organization (discussed in paragraph M.6.7).

The provision for adequate speech intelligibility, the protection of employees working within the boundaries of the noisy building, and also the confinement of the disturbing noises within their legitimate premises can be accomplished by the use of suitable sound insulating enclosures, described in Section N (S-157, S-158). It is important to consider the frequency distribution of the offending noise so that suitable enclosures can be selected with effective TL at these critical frequencies.

Figure M.7 lists recommended distances between various noise producing industries and residential areas.

Various aspects of the control of industrial noise have been presented in numerous articles (S-139, S-140, S-142, S-143, S-144, S-145, S-146, S-147, S-148, S-151, S-152, S-154, S-156, S-159, S-161, S-162, S-165, S-168, S-169, S-170, S-171, S-172, S-173, S-174).

References

relative to Section S: "Practical Noise Control"

(See list of abbreviations on page 1)

Auditoria

Articles, papers, reports

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+ S-2 As to the noise control of various auditoria see also following references: H-39, N-78.

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Articles, papers, reports

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+ S-5 Noise control in Recording, Television and Motion Picture Studios by W.B. Snow. Noise Control, Vol. 3, No. 3, May 1957, p. 19-22.

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Residential Buildings

Books, booklets, chapters of books

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Articles, papers, reports, bulletins

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